Original Article

A theoretical analysis of longitudinal temporomandibular joint compressive stresses and mandibular growth

Riddhi J. Desai[a]; Laura R. Iwasaki[b]; Sohyon M. Kim[c]; Hongzeng Liu[d]; Ying Liu[e]; Jeffrey C. Nickel[f]

ABSTRACT

Objectives: To determine if temporomandibular joint (TMJ) compressive stresses during incisor biting (1) differed between growing children over time, and (2) were correlated with Frankfort Horizontal-mandibular plane angle (FHMPA, °) and ramus length (Condylion-Gonion (Co-Go), mm).

Materials and Methods: Three-dimensional anatomical geometries, FHMPA and Co-Go, were measured longitudinally from lateral and posteroanterior cephalographs[1] of children aged 6 (T1), 12 (T2), and 18 (T3) years. Geometries were used in numerical models to estimate subject-specific TMJ eminence shape and forces for incisor bite-forces of 3, 5, and 8 Newtons at T1, T2, and T3, respectively. TMJ compressive stresses were estimated via two steps: First, TMJ force divided by age-dependent mandibular condylar dimensions, and second, modified by loading surfaces' congruency. Analysis of variance and Tukey honest significant difference post-hoc tests, plus repeated measures and mixed effects model analyses were used to evaluate differences in variables between facial groups. Regression analyses tested for correlation between age-dependent compressive stresses, FHMPA, and Co-Go.

Results: Sixty-five of 842 potential subjects had T1-T3 cephalographs and were grouped by FHMPA at T3. Dolichofacial (FHMPA $\geq$ 27°, n = 36) compared to meso-brachyfacial (FHMPA $<$ 27°, n = 29) subjects had significantly larger FHMPA at T1-T3, shorter Co-Go at T2 and T3 (all $P < .01$), and larger increases in TMJ compressive stresses with age ($P < .0001$). Higher compressive stresses were correlated with larger FHMPA (all $R^2 \geq 0.41$) and shorter Co-Go (all $R^2 \geq 0.49$).

Conclusions: Estimated TMJ compressive stress increases from ages 6 to 18 years were significantly larger in dolichofacial compared to meso-brachyfacial subjects and correlated to FHMPA and Co-Go. (*Angle Orthod.* 2022;92:11–17.)

KEY WORDS: Temporomandibular joint; Longitudinal growth; Compressive stress; Facial phenotype; Dolichofacial; Brachyfacial

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INTRODUCTION

Recent survey results[2] indicated >9% of US children aged 8–17 years are treated for malocclusions at costs of >$9.5 billion annually.[3,4] This treatment represented 14.5% and the third largest category of dental procedures for people <20 years of age.[4] At least 30% of malocclusions involved skeletal jaw discrepancies[5] where dentofacial orthopedic therapies to promote or arrest jaw growth were indicated. However, excluding patient non-compliance, 13%–36% of mandibular growth enhancement therapies failed to correct the malocclusion[6,7] because the mandibular growth achieved was insufficient to correct the jaw discrepancy. Furthermore, less-than-ideal results may require surgery, which adds morbidity risks and costs.

The spectrum of human dentofacial phenotypes includes dolichofacial vs brachyfacial features with proportionally long-narrow vs short-wide faces, steep vs flat mandibular plane angles, and relatively short vs long ramus lengths (Co-Go, Figure 1). Less mandibular condyle growth,[8,9] poorer prognoses for dentofacial orthopedic treatment,[10,11] and, thus, increased liability for risks and costs are expected in dolichofacial compared to brachyfacial phenotypes. Improved understanding of the factors that affect jaw growth and if these are different in different phenotypes could improve dentofacial orthopedic therapies.

Variations in functional temporomandibular joint (TMJ) loading patterns in different dentofacial phenotypes have been described.[12–14] In part, these variations can result from age-related changes in craniomandibular mechanics and occlusal forces. In addition, in vitro experiments suggested, depending on loading force magnitudes and frequencies, it was possible to inhibit or stimulate mandibular condylar cartilage growth.[15] Based on this, estimated compressive stresses of 0.05–0.10 megapascal (MPa) are associated with inhibition, while those below this threshold are associated with stimulation. Mechanoresponsive genes[16] may be the transduction mechanism responsible. In humans, average TMJ compressive stresses increase from ages 0 to 25 years due to changes in jaw functions with dental development (eg, suckling, incision, chewing), and increased masticatory muscle strength.[17] Recently, a study of jaw mechanics in dolichofacial and brachyfacial phenotypes found no TMJ load differences at age 6 years; however, TMJ loads at 12 and 18 years were up to 20% larger in dolichofacial than brachyfacial subjects.[12] Theoretically, between 10 and 15 years of age, average TMJ compressive stresses reach the critical threshold of 0.05–0.10 MPa.[17] That is, higher compressive stresses due to increased masticatory muscle strength with maturation or increased frequency of loading, or both, may inhibit secondary cartilage growth of the mandibular condyle, thus, limiting further increases in ramus length.

This retrospective study addressed the need for more longitudinal quantitative human data to inform about factors that could enhance or impede jaw growth and dentofacial orthopedics, and if these were different in different phenotypes. The specific objectives were to determine if TMJ compressive stresses during incisor biting (1) differed between growing children over time, and (2) were correlated with Frankfort Horizontal-to-mandibular plane angle (FHMPA, °) and ramus length (Co-Go, mm).

MATERIALS AND METHODS

Anatomical data were obtained by reviewing all available cases in the web-based American Association of Orthodontists Foundation Legacy Collection.[1] Sample inclusion criteria were lateral and posteroanterior cephalographs at ages 6 (T1), 12 (T2), and 18 (T3) years with identifiable landmarks for measurement of FHMPA and Co-Go (Figure 1). Cephalographs were downloaded and analyzed using software (Dolphin, Dolphin Imaging & Management Solutions, Chatsworth, CA; MATLAB, MathWorks, Natick, MA) and fiducial points to correct for magnification.

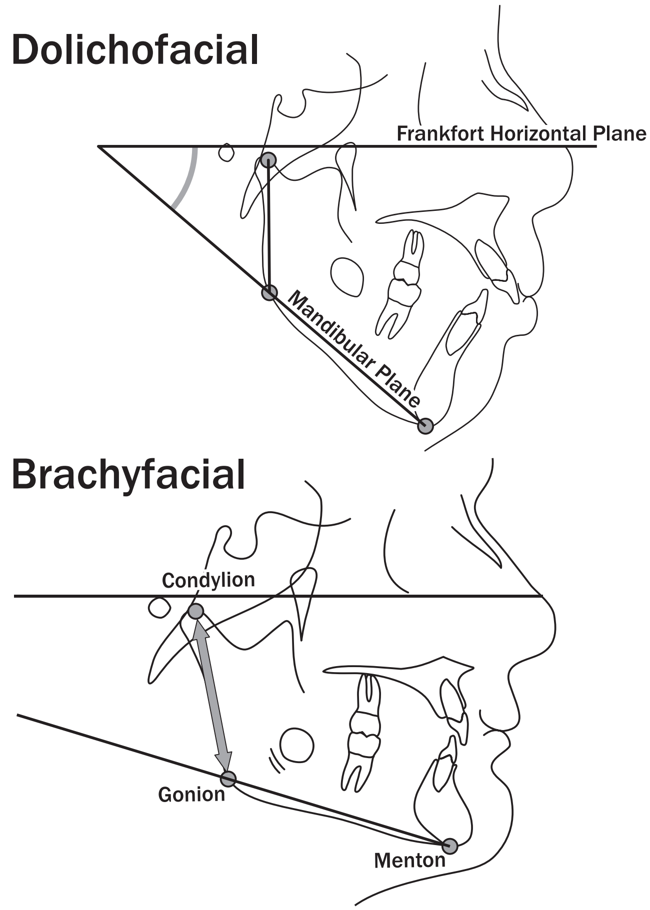

Figure 1. Dentofacial phenotype examples. Distinguishing features include relatively shorter Condylion-Gonion distance and steeper Frankfort Horizontal-mandibular plane angle in the dolichofacial compared to brachyfacial phenotype. Modified with permission.[17]

Cephalographs of each case at T1-T3 also provided a three-dimensional geometry file, which was used in numerical models[18] to predict (1) subject-specific TMJ eminence shape based on the objective of minimization of TMJ loads,[19] and (2) TMJ forces during static biting on incisor teeth (Figure 2) based on the objective of minimization of muscle effort, at average ages of 6, 12, and 18 years. These objective functions produced accurate results using these approaches in validation studies.[19,20] As previously described,[12] the geometry file contained the rectilinear (x, y, z) coordinates of the mandibular incisors, canines, and molars; right and left condyles; and origins and insertions of the masseter, temporalis, medial and lateral pterygoid, and digastric

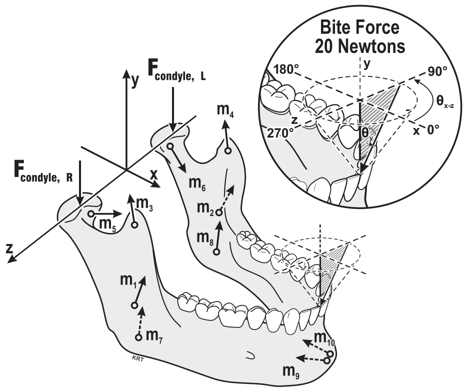

Figure 2. Three-dimensional individual-specific anatomy (geometry file) for numerical modeling. Left: positions of joints ($F_{condyle}$, R = right, L = left), and five masticatory muscle pairs ($m_{1,2}$ = masseter, $m_{3,4}$ = anterior temporalis, $m_{5,6}$ = lateral pterygoid, $m_{7,8}$ = medial pterygoid, $m_{9,10}$ = anterior digastric muscles). Muscle force vector directions are determined by jaw position and corresponding craniomandibular anatomy. Numerical models predict muscle- and joint-force magnitudes and joint-force directions for a given objective and applied force; eg, Right: modeled range of bite-forces, according to θ_{xz}, parallel to occlusal plane (0–350°), and θ_y (0–40°). Modified with permission.[30]

muscles. Coordinates were determined by consensus of two judges who were calibrated using cadaveric material.[18] Each subject's T1-T3 geometry files were used in the numerical model (1) to prescribe a third order polynomial, which depicted the T1-T3 sagittal TMJ eminence shapes using published methods.[18] In brief, this model predicted TMJ force directions for bilateral vertical biting at molars to incisors in 20 sequential steps, where mandibular positions represented retrusion to protrusion, respectively. For equilibrium at each position, the eminence surface must be perpendicular to the force; therefore, the series of 20 lines perpendicular to the predicted TMJ forces were delineated and fit to a polynomial. The individual-specific eminence shape and geometry files at each time point were then used in a numerical model (2) that calculated masticatory muscle and TMJ forces for static biting centered on the incisors for bite forces of 3 (T1), 5 (T2), and 8 (T3) N to reflect age-related increases. These incisor bite-forces were based on published data[21] and ambulatory recordings from children aged 13.3–17.6 years, which showed that peak loading forces on the mandible rarely exceeded 8 N.[22] Bite forces were applied over a large range of angles, accounting for those likely to occur during normal jaw activities: 0–350° in the occlusal plane (θ_{xz}) in 10° steps, and vertical angles (θ_y) ranging from 0–40° in 5°steps (Figure 2). The incisor biting was centered; therefore, predicted left and right TMJ forces were symmetrical and equal. Overall mean predicted TMJ force was calculated for the full range of biting angles for each subject and time point.

TMJ compressive stresses (force/area) were estimated via a two-step process to determine subject- and age-specific localized condylar loading area during incisor biting. First, age-related anteroposterior and mediolateral dimensions of 420 mandibular condyles from 210 children[23] were used to construct polynomial regressions of anteroposterior ($y = -0.012x^2 + 0.393x + 5.959$) and mediolateral ($y = 0.004x^3 - 0.143x^2 + 1.930x + 8.237$) condylar growth trajectories, where y was dimension (mm) and x was age (years). These regressions were employed to determine general condylar loading areas (anteroposterior × mediolateral dimensions, mm^2) at ages of 6 (T1), 12 (T2), and 18 (T3) years. Second, the articular surfaces' congruency (shape-matching) was considered because the ratio of these congruencies with the mandible in protruded vs retruded positions (y = congruency constant) is related to the steepness of the human sagittal TMJ eminence slope (x, expressed relative to 1.0 = largest slope for a given data set), according to: $y = 0.72x^2 - 1.82x + 1.45$.[24] Smaller slopes are associated with larger congruency constants. For each subject and time point, the model-predicted eminence slope (≤ 1.0) was used in the equation to calculate a congruency constant, which was then multiplied by the general condylar loading area for the appropriate age to produce a subject- and age-specific estimation of localized condylar loading area during incisor biting. Thus, TMJ compressive stress (MPa) during incisor biting was calculated by dividing mean predicted TMJ force by this loading area for each subject at each time point.

One judge measured Frankfort Horizontal (Porion-Orbitale) mandibular plane (Gonion-Menton) angle and Co-Go in 15 randomly selected cases and repeated these measurements on a different day to calculate intraclass correlation coefficients (ICC) and 95% confidence intervals for each variable via an absolute-agreement, two-way mixed-effects model. Subjects were grouped empirically based on FHMPA $\geq 27°$ and $< 27°$, defined as dolichofacial and meso-brachyfacial subjects, respectively. Analysis of variance and Tukey honest significant difference post-hoc tests evaluated time points and group differences in age (years), FHMPA (°), and Co-Go (mm) where $P < .01$ defined significance. Regression analyses tested for correlation between TMJ compressive stress and (1) T1-T3 FHMPA, and (2) Co-Go normalized to the longest within the same sex to address differences in overall size. Repeated-measures and mixed-effects model analyses compared longitudinal patterns of change in Co-Go and compressive stress by group and sex where $P < .05$ defined significance.

Table 1. Means and Standard Deviations for Age, Frankfort Horizontal-Mandibular Plane Angle (MPA), and Ramus Length (Co-Go) at Three Time Points (T1, T2, T3) in Dolichofacial and Mesobrachyfacial Groups With Results From Between-Group Comparisons Where Significant Differences Were Defined by $P < .01$ (*)

Time Point	Variable	Dolichofacial Group, Mean ± Standard Deviation	Meso-brachyfacial Group, Mean ± Standard Deviation	*P* Value
T1	Age (year)	6.3 ± 0.6	6.2 ± 0.6	.52
	MPA (°)	30.1 ± 2.9	24.3 ± 3.3	3.5E-09*
	Co-Go (mm)	46.2 ± 3.5	47.5 ± 3.0	.16
T2	Age (year)	12.0 ± 0.2	12.1 ± 0.1	.01
	MPA (°)	30.3 ± 2.9	22.0 ± 3.1	7.7E-16*
	Co-Go (mm)	53.0 ± 3.7	55.6 ± 3.3	.004*
T3	Age (year)	18.1 ± 0.9	18.3 ± 1.0	.42
	MPA (°)	30.7 ± 2.9	19.1 ± 3.9	9.1E-18*
	Co-Go (mm)	59.3 ± 5.6	64.6 ± 4.9	1.4E-4*

Abbreviations: Co-Go indicates ramus length; MPA, Frankfort horizontal-mandibular plane angle; T1, time point 1; T2, time-point 2; T3, time-point 3; * significant difference between groups ($P < .01$).

RESULTS

Of 842 available cases,[1] 65 met inclusion criteria and represented 36 dolichofacial subjects (24 females, 12 males) and 29 meso-brachyfacial subjects (12 females, 17 males) from the Burlington, Mathews, and Oregon Growth Studies. Mean ages at T1-T3 were similar in dolichofacial and meso-brachyfacial cases (Table 1). Repeated cephalometric measurements for FHMPA and Co-Go showed ICC (with 95% confidence intervals) of 0.84 (0.58–0.94) and 0.97 (0.90–0.99), respectively. Mean FHMPA and was significantly larger (all $P \leq 3.5E-09$) in dolichofacial compared to meso-brachyfacial groups at all time points (Table 1). Mean Co-Go was significantly shorter at T2 and T3 (all $P \leq .004$) in dolichofacial compared to meso-brachyfacial groups (Table 1). At T1-T3, TMJ eminence slopes and FHMPA were positively correlated (Figures 3A,B,C; all $R^2 \geq 0.76$).

Longitudinal analyses showed increases in Co-Go between 6 and 18 years of age were significantly larger in meso-brachyfacial compared to dolichofacial groups ($P = .006$) and males compared to females ($P = .004$), where trends were exponential for males and logarithmic for females (data not shown). For incisor biting, increases in TMJ compressive stresses with age were significantly larger in dolichofacial compared to meso-brachyfacial subjects ($P < .0001$, Figure 4). Positive non-linear longitudinal relations between TMJ compressive stresses and FHMPA (all $R^2 \geq 0.41$) resulted where, at T3, a majority of subjects, especially females, had TMJ compressive stresses above the 0.05 MPa threshold and those who did not tended to have low FHMPA (Figure 5). Mixed effects models verified that TMJ compressive stresses significantly increased over T1-T3 and that the patterns were significantly different between sexes, with stresses not different at T1 but significantly larger in males than females at T2 ($P = .001$) and significantly larger in females than males at T3 ($P = .027$). Additionally, those with higher FHMPA at T2 showed more significant increases in TMJ compressive stress over time ($P < .0001$). Positive non-linear relations between TMJ compressive stresses

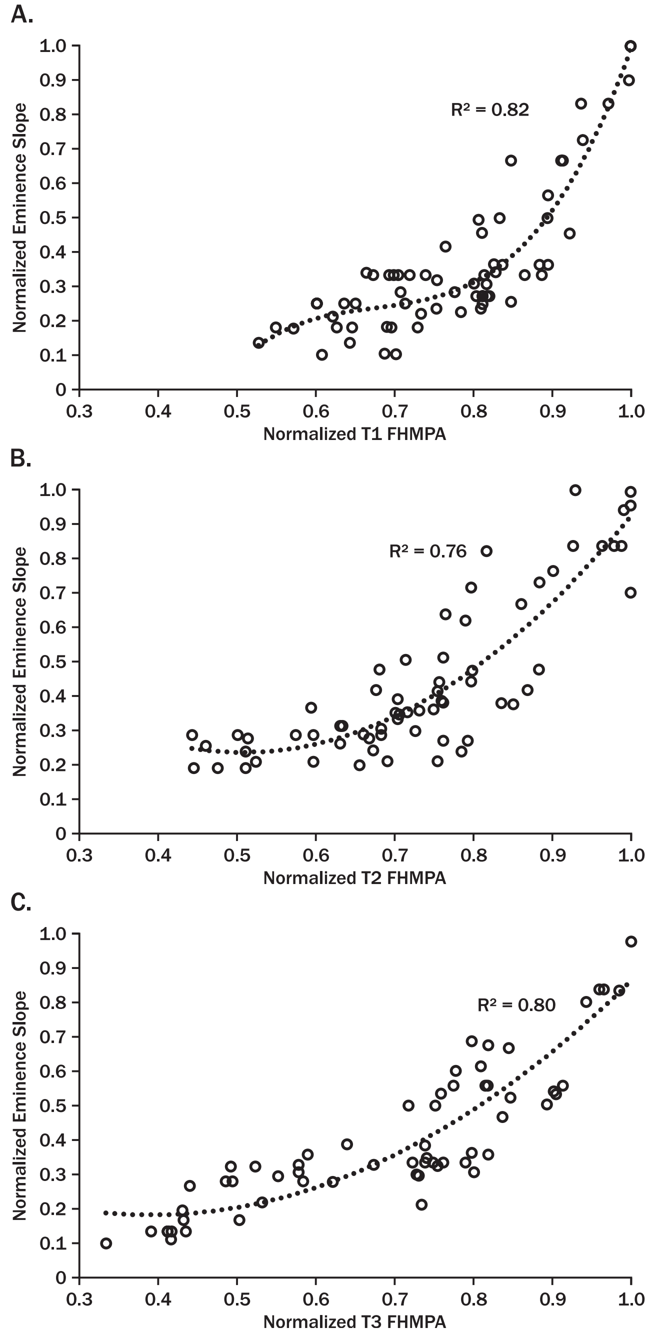

Figure 3. Temporomandibular joint (TMJ) eminence slope versus Frankfort Horizontal-mandibular plane angle (FHMPA) for three time points, (A) T1, (B) T2, (C) T3. Within each time point, slope and angle values were normalized to peak value of all subjects for slope and angle, respectively, to address differences in overall size between subjects.

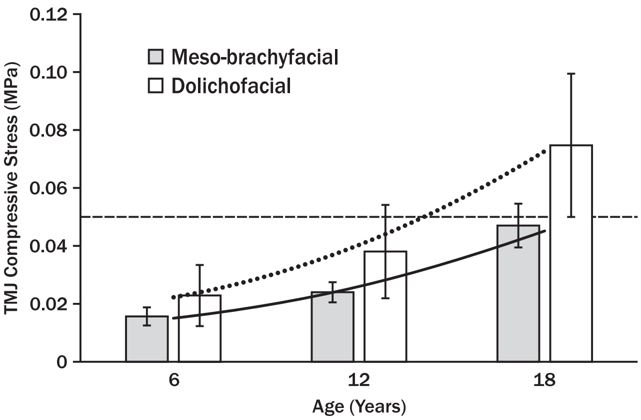

Figure 4. Average estimated temporomandibular joint (TMJ) compressive stress (MPa) vs age (years) in dolichofacial and meso-brachyfacial groups, where pattern of change with age was significantly different between groups ($P < .0001$). Dashed line indicates theoretical threshold of stress that is associated with inhibition of condylar cartilage growth.[20]

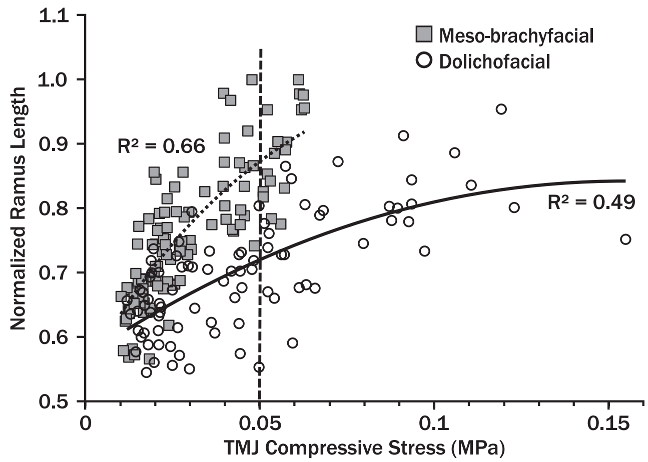

Figure 6. Ramus length (Co-Go) normalized within sex versus estimated temporomandibular joint (TMJ) compressive stresses during incisor biting in meso-brachyfacial and dolichofacial children from three time points (T1-T3). Dashed line indicates theoretical threshold of stress that is associated with inhibition of condylar cartilage growth.[20]

and normalized Co-Go resulted for both dolichofacial ($R^2 = 0.49$) and meso-brachyfacial ($R^2 = 0.66$) groups (Figure 6). In addition, mixed effects models showed those with lower TMJ compressive stresses at T2 had more significant increases in Co-Go over time ($P = .017$).

DISCUSSION

Differences in mandibular condylar growth over time between dolichofacial and meso-brachyfacial children were confirmed by this retrospective longitudinal study. The results suggested that higher TMJ compressive stresses at T2 and T3 may contribute to shorter Co-Go in dolichofacial compared to meso-brachyfacial subjects. The findings were consistent with data from condyle explant studies[15] where increased static compressive stresses resulted in cessation of mandibular cartilage growth. Compressive stresses in some dolichofacial subjects appeared to have reached the inhibitory threshold as early as age 12 years.

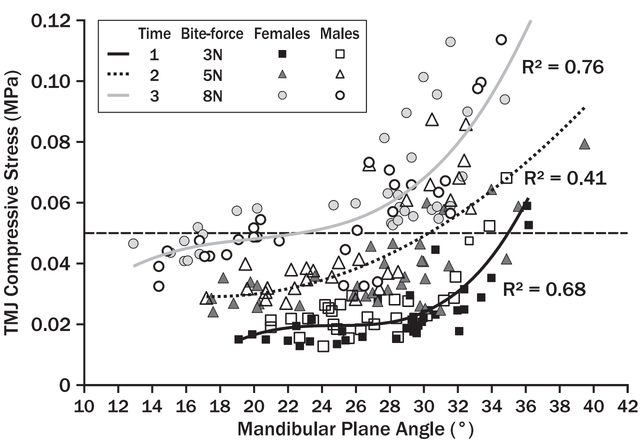

Figure 5. Estimated temporomandibular joint (TMJ) compressive stress during incisor biting versus mandibular plane angle for three time points, where applied bite forces were 3, 5, and 8 Newtons (N) for T1, T2, and T3, respectively; symbols are filled for females and unfilled for males; and dashed line indicates theoretical threshold of stress that is associated with inhibition of condylar cartilage growth.[20]

The data supported the premise that differing orthopedic approaches may be appropriate to address mandibular retrognathism in dolichofacial and meso-brachyfacial children. The mandibular protrusion associated with orthopedic appliances may produce greater incongruency between TMJ loading surfaces in dolichofacial children, resulting in static compressive stresses >0.05 MPa at an earlier age than their meso-brachyfacial counterparts. Higher compressive stresses in the current study were due, in part, to decreased shape-matching of the TMJ loading surfaces in individuals with higher FHMPA. If so, reducing the magnitude of mandibular protrusion during orthopedic therapy in dolichofacial children may reduce compressive stresses that would otherwise limit the growth response of the mandibular condyle. This may also support a recent meta-analysis[25] of functional appliance clinical outcomes, which concluded that an incremental advancement protocol produced better skeletal growth results.

If orthopedic interventions aimed at promoting mandibular growth are most efficacious during adolescent accelerated growth, monitoring for accelerated growth in dolichofacial patients may be especially important given that the window of “growth optimization” may be shorter compared to meso-brachyfacial patients. For example, at age 12 years (Figure 4), average compressive stresses were below the 0.05

MPa threshold but 58% higher in the dolichofacial compared to the meso-brachyfacial group. The current data (Figure 4) suggested that a moderate reduction in bite forces by 15%–20% at age 12 years may, theoretically, keep TMJ compressive stresses <0.05 MPa and add 12–18 months to the "growth optimization" window.

The current study compared TMJ compressive stresses between facial phenotypes during the same incisor biting tasks. Maximum bite-force capabilities may be higher in children with brachyfacial compared to dolichofacial features when measured in laboratory conditions with biofeedback,[26] but ordinary jaw-use behaviors outside of the laboratory, such as incision and chewing, do not elicit maximum bite forces. In addition, recently reported data recorded during the day and night in dolichofacial and brachyfacial children in their usual environments showed that magnitudes of tooth loading forces were rarely >8 N and not significantly different between the two groups,[22] but brachyfacial compared to dolichofacial children more frequently produced low-amplitude mandibular loads.

This retrospective project had limitations because the accuracy of model-predictions and compressive stresses could not be validated and the sample was restricted to available records, so comparison between equal groups that were balanced for sex and had FHMPA distinguishing dolichofacial, brachyfacial, and mesofacial phenotypes was not possible. Also, the current study did not differentiate age-dependent changes in TMJ loading areas between sexes and it focused on static compressive stresses, which do not reflect the effects of magnitude and frequency of mechanical work imposed on TMJ cartilage due to perpendicular (compressive) and tangential (shear) stresses. These shortcomings can be addressed through a prospective study to characterize the variables relevant to growth of the mandibular condyles that are individual-specific by employing longitudinal imaging of the TMJ and craniofacial anatomy, in combination with data about jaw-loading behaviors from jaw muscle electromyography, TMJ forces from numerical modeling, and three-dimensional joint contact mechanics from dynamic stereometry.[27] These approaches have been combined to give TMJ "mechanobehavior scores" in living humans[14,17,22] and have potential to improve understanding of factors that influence the clinical outcomes of functional appliances in children.

CONCLUSIONS

- Estimated TMJ compressive stress increases from ages 6 to 18 years were significantly larger in dolichofacial compared to meso-brachyfacial subjects and correlated to mandibular plane angle and ramus length.
- The results suggest that higher compressive stresses at younger ages and throughout the growth period may be a mechanism that limits the duration and magnitude of mandibular condylar growth in dolichofacial compared to meso-brachyfacial children.

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