Original Article

Mechanobehavior and mandibular ramus length in different facial phenotypes

Paige Covington Riddle[a]; Jeffrey C. Nickel[b]; Ying Liu[c]; Yoly M. Gonzalez[d]; Luigi M. Gallo[e]; R. Scott Conley[f]; Robert Dunford[g]; Hongzeng Liu[h]; Laura R. Iwasaki[b]

ABSTRACT

Objectives: To test the hypotheses that mechanobehavior scores (MBS) were correlated with mandibular ramus lengths (Co-Go) and differed between facial phenotypes.

Materials and Methods: Subjects gave informed consent to participate. Co-Go (mm), mandibular plane angles (SN-GoGn, °), and three-dimensional anatomy were derived from cephalometric radiography or cone beam computed tomography. Temporomandibular joint (TMJ) energy densities (ED) (mJ/mm^3) were measured using dynamic stereometry and duty factors (DF) (%) were measured from electromyography, to calculate MBS ($= ED^2 \times DF, \left(\frac{mJ}{mm^3}\right)^2 \%$) for each TMJ. Polynomial regressions, K-means cluster analysis, and analysis of variance (ANOVA) with Tukey post-hoc tests were employed.

Results: Fifty females and 23 males produced replete data. Polynomial regressions showed MBS were correlated with Co-Go (females, $R^2 = 0.57$; males, $R^2 = 0.81$). Cluster analysis identified three groups ($P < .001$). Dolichofacial subjects, with shorter normalized Co-Go, clustered into two subgroups with low and high MBS compared to brachyfacial subjects with longer Co-Go. SN-GoGn was significantly larger ($P < .03$) in the dolichofacial subgroups combined (33.0 ± 5.9°) compared to the brachyfacial group (29.8 ± 5.5°).

Conclusions: MBS correlated with Co-Go within sexes and differed significantly between brachyfacial and dolichofacial subjects. (*Angle Orthod.* 2020;90:866–872.)

KEY WORDS: Human; Craniofacial form; TMJ; Jaw mechanics; EMG; Masticatory muscles

INTRODUCTION

Distinctive human facial characteristics include mandibular ramus lengths and mandibular plane angles that are relatively short and steep, respectively, in dolichofacial phenotypes and relatively long and flat, respectively, in brachyfacial phenotypes (Figure 1). Mandibular condyle growth affects ramus length, where growth is less in amount and expressed more

[a] Private Practice, Leawood, Kansas, USA.
[b] Professor-Provisional, Department of Orthodontics, School of Dentistry, Oregon Health & Science University, Portland, Oregon, USA; and Research Associate Professor, Department of Oral Diagnostic Sciences, University at Buffalo, School of Dental Medicine, Buffalo, New York, USA.
[c] Assistant Professor, Department of Biostatistics and Epidemiology, College of Public Health, East Tennessee State University, Johnson City, Tennessee, USA.
[d] Associate Professor, Department of Oral Diagnostic Sciences, University at Buffalo, School of Dental Medicine, Buffalo, New York, USA.
[e] Professor, Physiology and Biomechanics of the Masticatory System, Dental School, Faculty of Medicine, University of Zurich, Zurich, Switzerland.
[f] Private Practice, Washington, Pennsylvania, USA.
[g] Statistician, University of Buffalo Microbiome Center, School of Dental Medicine, Buffalo, New York, USA.
[h] Senior Research Associate, Department of Orthodontics, School of Dentistry, Oregon Health & Science University, Portland, Oregon, USA.
Corresponding author: Dr Laura R. Iwasaki, Chair, Department of Orthodontics, School of Dentistry, Oregon Health & Science University, SD-ORTHO, 2730 SW Moody Ave, Portland OR 97211
(e-mail: iwasaki@ohsu.edu)

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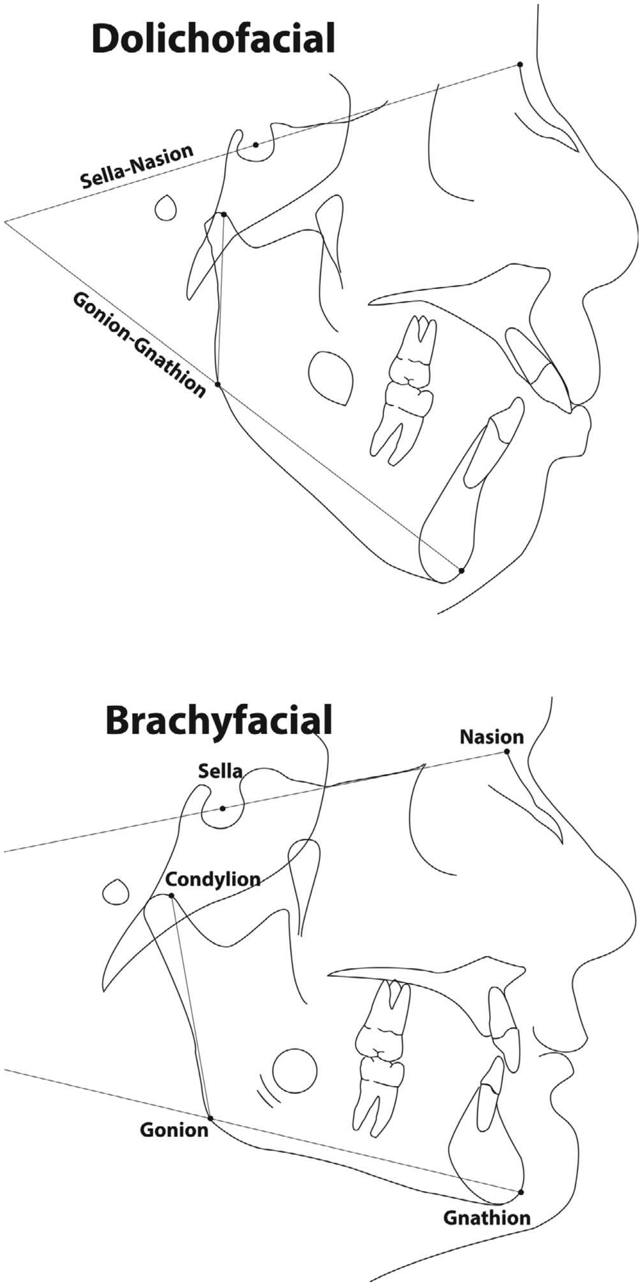

Figure 1. Mandibular ramus length (Condylion-Gonion, mm) and Sella-Nasion-to-mandibular plane (SN-Gonion-Gnathion) angle (°) shown in example facial phenotypes.

vertically[1,2] and has poorer prognoses for dentofacial orthopedic treatment in dolichofacial compared to brachyfacial patients.[3,4]

Critical barriers to improved success rates for dentofacial orthopedic treatments are the lack of foundational data to inform and direct research that will improve understanding of what specific factors enhance or impede mandibular condyle growth and whether these factors are different between dolichofacial and brachyfacial phenotypes. Orthopedic treatment, on average, can achieve about 2 mm/y of increased mandibular growth compared to controls, with significantly greater effects in the pubertal compared to pre- and post-pubertal stages, and with similar results no matter the appliance design.[5,6] These average amounts of enhanced mandibular growth are insufficient, as demonstrated by the reported 13%-36% of outcomes that are less than adequate.[7,8] Evidence is lacking to understand why some cases are successful and others are not.

The three-dimensional shapes and relationships of growing, loaded temporomandibular joint (TMJ) surfaces, are affected by in situ mechanics.[9,10] Mandibular forward positioning, as in dentofacial orthopedic treatment, likely decreases TMJ hard tissue surface-matching.[11] This increases TMJ stress-concentrations (MPa), leading to increased energy densities (ED, mJ/mm^3), which are measures of the mechanical work input per volume between condyle and temporal eminence loading areas. Mechanical environment characterization is critical to the mandible's unique growth physiology. In particular, fibrocartilage stem cells in the mandibular condyle perichondrium[12] respond to the mechanical environment through mechanosensitive genes such as Indian hedgehog (IHH), sclerostin (SOST), fibroblast growth factor (FGF), transforming growth factor beta (TGFB), and wingless-related integration site (WNT).[13] Additionally, oxygen consumption rates are greater than or equal to five times higher in stem cell-derived fibrochondrocytes than hyaline cartilage chondrocytes and volume-based cell densities are four times greater in TMJ fibrocartilage than hyaline cartilage.[14] These features together make glucose and oxygen gradients of the growing mandibular condyle particularly vulnerable to the magnitude and frequency of jaw loading behaviors which can be measured via TMJ ED and jaw muscle duty factors (DF, muscle activity duration/total recording time, %), respectively. Current dentofacial orthopedic therapies attempt to influence mandibular growth through mechanosensitive stem cells and fibrochondrocytes, but lack foundational data about jaw mechanics and behaviors (mechanobehavior) in individuals with distinctly different phenotypes and their longitudinal treatment outcomes. How much TMJ loading occurs during jaw use and how often this loading behavior occurs are distinct individual-specific factors that can each affect mandibular growth. How orthopedic appliances affect these factors is also unknown.

The variables of TMJ ED and DF have been combined as a mechanobehavior score (MBS $= ED^2 \times DF, \left(\frac{mJ}{mm^3}\right)^2 \%$) previously, and showed that MBS were significantly higher in women with, compared to without, TMJ disc displacement.[15] As a first step to characterize variables that influence mandibular condyle ontogeny,[10] the current study investigated MBS and mandibular ramus length (Condylion-Gonion [Co-Go], mm) in adults with varying facial phenotypes. That is, the hypotheses tested were that MBS: (1) was correlated with Co-Go and (2) differed between facial phenotypes.

MATERIALS AND METHODS

Subjects were ≥18 years old; had all first molars, canines, and incisors with relatively symmetric craniofacial features; and their rights were protected during study participation by protocols approved by the University at Buffalo and University of Missouri-Kansas City Institutional Review Boards. Exclusion criteria included allergies to study materials, large dental restorations, inability to read and follow auditory commands, history of diagnosed musculoskeletal disease or TMJ trauma, radiographic evidence of degenerative osseous TMJ changes, and pregnancy.

Perspective projection lateral cephalograms were derived from digital radiographs or cone beam computed tomography (CBCT) images made in the same university clinic. An operator (PCR), who was blinded to the mechanobehavioral data, used the lateral cephalograms and software (Dolphin 3-dimensional Image System, version 11.9.07.24 Premium, Chatsworth, CA) to correct magnification so that actual and imaged midsagittal plane structures were 1:1, and then to trace, identify landmarks (bisected if bilateral), and make measurements. Landmarks included condylion (Co, superoanterior-most condylar point), gnathion (Gn, anteroinferior-most chin point), gonion (Go, posteroinferior-most gonial angle point), nasion (N, midsagittal junction of nasal and frontal bones), and sella (S, center of pituitary fossa), for measurement of mandibular plane angle (SN-GoGn, °) and ramus length (Co-Go, mm) (Figure 1).

Numerical modelling of TMJ forces (F_{normal}) during loading of mandibular teeth required each subject's craniomandibular anatomy, which was quantified using lateral and posteroanterior cephalograms or CBCT images, and comprised the three-dimensional positions of the mandibular condyles, incisors, canines, molars, and origins and insertions of masseter, temporalis, lateral and medial pterygoid, and digastric muscles (Figure 2).[16] The numerical model calculated F_{normal} based on an objective function of minimization of muscle effort during biting unilaterally on the right and left mandibular canines using 20 N applied at a range of biting angles (Figure 2). F_{normal} was determined for this range, averaged for right and left TMJs, then used as previously described,[15–17] in:

Equation 1:

$$F_{traction} = F_{normal} \times a^{\left(-0.5\left[\left(\frac{\{x-x_0\}}{b}\right)^2 + \left(\frac{\{y-y_0\}}{c}\right)^2\right]\right)}$$

Equation 2:

$$\text{Energy density} = \frac{(F_{traction} \times D)}{Q}$$

Equation 1 was derived from laboratory experiments[18] that estimated the plowing tractional forces ($F_{traction}$) associated with TMJ stress-field movement during symmetrical jaw closing, where *a, b, c,* x_0, and y_0 are constants, $x =$ aspect ratio x compressive strain[3] and $y_0 =$ stress-field translation velocity. Equation 2 estimated ED (mJ/mm^3). Dynamic stereometry provided the measurements of *y*, aspect ratio (a/h), compressive strain (Δh /h), stress-field translation distance (ΔD), and TMJ disc volume (*Q*) needed for the equations.

Dynamic stereometry[17] results in real-time animations of the TMJ contact relationships using three-dimensional anatomy from magnetic resonance (MR) images combined with kinematics from jaw position tracking. Specifically, a 1.5-T MR machine and surface coils of 12 cm radius were used to image the TMJs and head reference system (with three MR-contrast spheres) attached to a custom occlusal registration appliance worn by each subject (Figure 3A). In a laboratory setting, right- and left-side jaw positions were tracked by a linear array of cameras that recorded the positions of light-emitting diodes attached to the head reference system and each subject's maxilla and mandible via the teeth (Figure 3A). Static biting, with the occlusal registration appliance and head reference system in place, and 10 symmetrical jaw opening-closing movements without this appliance and reference system were recorded. The reconstructed TMJ anatomy captured by MR images was combined with corresponding real-time jaw positions during opening-closing movements via the common reference system, which resulted in animations of the contact relationships within each TMJ (Figure 3B,C). Variables of interest in each TMJ in all subjects were determined over 5-ms time intervals and used in the equations to calculate ED (mJ/mm^3) from right and left TMJs, which were then averaged.

Magnitudes and durations of jaw muscle activities were measured using ambulatory electromyography (EMG) calibrated via bite force vs EMG data from each muscle and subject as previously reported.[15,19] Subjects were trained to place surface EMG electrodes over either the right or left masseter and temporalis

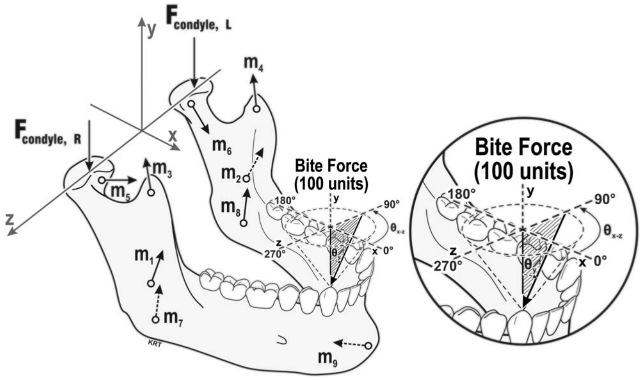

Figure 2. Three-dimensional anatomy for numerical modeling included force vectors for: TMJs ($F_{condyle}$; R = right, L = left), five muscle pairs ($m_{1,2}$ = masseter, $m_{3,4}$ = anterior temporalis, $m_{5,6}$ = lateral pterygoid, $m_{7,8}$ = medial pterygoid, $m_{9,10}$ = anterior digastric), and biting characterized by occlusal plane (θ_{xz}, 0–350°) and vertical (θ_y, 0–40°) angles. Modified[16] with permission.

muscles plus the mastoid process (ground), and to connect and use portable recorders. The recorders amplified (1500x) and sampled (2000 Hz/channel) muscle activities, and saved the digital signals on data storage cards. Subjects were asked to record for 2 days and 2 nights, for at least 6 hours per session (Figure 4A,B). These data were processed using customized software (MATLAB, MathWorks, Natick, MA) to detect, delimit, and calculate root-mean-square values for EMG segments (mV) defined by 128 ms contiguous rectangular sliding Hamming windows. DF were defined as the cumulative time of jaw muscle activities relative to the total recording time (%). To characterize DF associated with muscle activity magnitudes, two laboratory sessions of static and dynamic bite force and EMG data (Figure 4C,D) were collected and plotted. From plots of bite force vs EMG data, slopes of linear regressions were calculated (mV/N) for masseter and temporalis muscles in each individual (Figure 4E). These slopes were applied in the ambulatory EMG analysis to determine DF for each muscle and subject for jaw muscle activity magnitudes associated with bite forces of $\geq$1 to $<$2 N; $\geq$2 to $<$5 N; and $\geq$5 to $<$10 N. This range was chosen because previous studies showed that self-recorded EMG in subjects' natural environments was rarely associated with bite forces $\geq$10 N.[19] DF were also determined for jaw muscle activity durations of $\geq$0.5 to $<$1 second; $\geq$1 to $<$2 seconds, $\geq$2 to $<$5 seconds, $\geq$5 to $<$10 seconds. DF were averaged for muscles and subject for daytime and for nighttime.

As previously reported, mechanobehavior scores (MBS) were calculated as the product of ED^2 and DF.[15] Polynomial regressions tested for significant correlations between the independent variables of TMJ ED (mJ/mm^3), jaw muscle DF (%), and MBS ($\left(\frac{mJ}{mm^3}\right)^2$%),

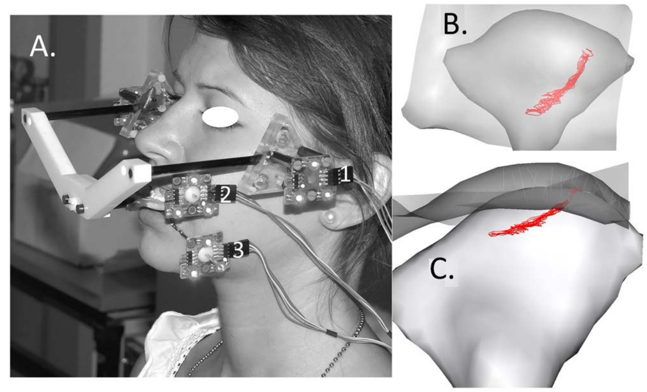

Figure 3. (A) Custom occlusal registration appliance with head reference system and contrast spheres for magnetic resonance imaging and (1) light-emitting diodes (LED) for jaw tracking. LED also attached to (2) maxillary and (3) mandibular labial tooth surfaces via custom brackets and glass ionomer cement. Left condyle and temporal fossa and eminence (disc not shown) in superior coronal (B) and frontal (C) views showing path of stress-field centroid (red) during symmetrical jaw closing. Modified[17] with permission.

and dependent variable of Co-Go (mm). To test for Co-Go phenotype differences associated with MBS, data were normalized within females and males to standardize for sex differences in scale. K-means cluster analysis tested normalized data for subject groupings. Analysis of variance and Tukey honest significant difference tests determined if there were group differences in Co-Go and SN-GoGn, with significance defined by $P < .05$.

RESULTS

Of 92 enrolled subjects (53 females, 39 males), 73 (50 females, 23 males) provided complete data and are reported upon. Average ages of females and males were 35.3 $\pm$ 12.9 and 34.3 $\pm$ 12.8 years, respectively. Co-Go measurements ranged from 47.6–94.5 mm. Females had significantly smaller ($P < .001$) average Co-Go (66.6 $\pm$ 7.2 mm) compared to males (73.4 $\pm$ 10.7 mm). SN-GoGn measurements ranged from 19.9°–48.8°, with no significant differences between females (31.7° $\pm$ 5.6°) and males (31.9° $\pm$ 6.8°).

Overall, average TMJ ED were 0.7–23.1 mJ/mm^3 with no significant differences between females (8.4 $\pm$ 4.7 mJ/mm^3) and males (9.5 $\pm$ 5.8 mJ/mm^3). Subjects produced 215 daytime and 216 nighttime EMG recordings with average durations of 7.0 and 7.8 hours, respectively. Average DF were 0.003%–10.8% during the day and 0.012%–9.3% during the night. There were no significant differences in DF between females (day: 1.2 $\pm$ 1.7%; night: 0.6 $\pm$ 1.4%) and males (day: 1.1 $\pm$ 1.1%; night: 0.7 $\pm$ 1.2%). Overall, cumulative jaw muscle activities associated with bite-forces $<$5 N showed the largest range of durations,

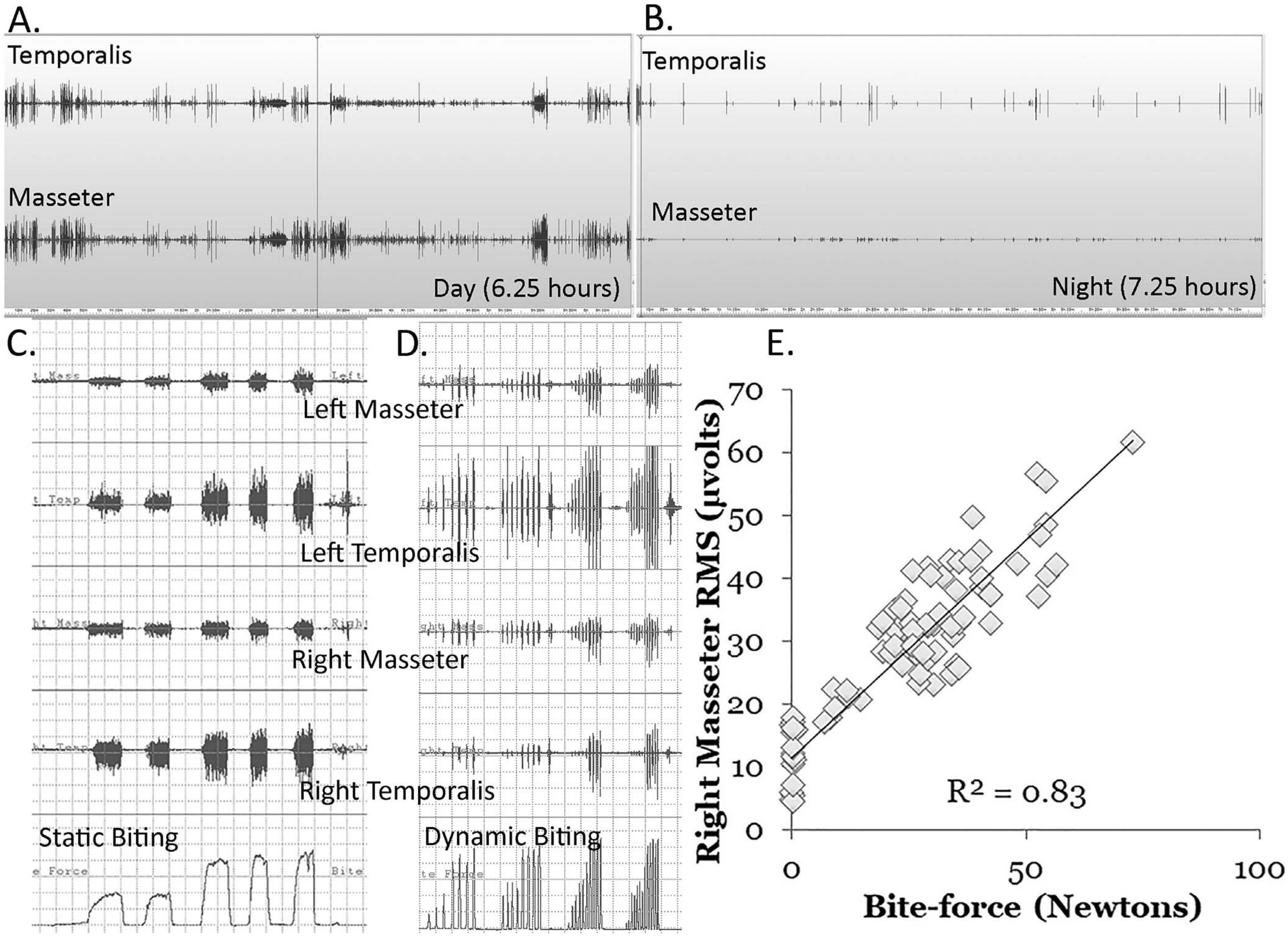

Figure 4. Ambulatory muscle activities recorded during one (A) day and (B) night. Laboratory muscle activities (top four rows) during (C) static and (D) dynamic bite forces (bottom row) over time (2-second intervals) produced (E) linear regression relations (root-mean-square [RMS] muscle activity [μvolts] per Newton of bite-force) for ambulatory EMG calibration by subject and muscle.

from 7.6 seconds to 44 minutes per 7 hours of EMG recording.

MBS based on average right and left TMJ ED and day- and nighttime DF were 0.5-328.2 $\left(\frac{mJ}{mm^3}\right)^2\%$ with no significant differences between females (63.9 ± 75.2 $\left(\frac{mJ}{mm^3}\right)^2\%$) and males (66.7 ± 88.9 $\left(\frac{mJ}{mm^3}\right)^2\%$). Polynomial regression analyses of MBS and Co-Go identified non-linear relationships in females ($R^2 = 0.57$) and in males ($R^2 = 0.81$), where peak Co-Go was associated with MBS from 20–100 $\left(\frac{mJ}{mm^3}\right)^2\%$ (Figure 5A). K-means cluster analysis of normalized data identified two subgroups with more dolichofacial features that had normalized MBS of <0.10 and >0.40 and significantly shorter (all $P < .001$) normalized Co-Go than the group with more brachyfacial features (Figure 5B). Among these groups defined by the cluster analysis, SN-GoGn was not significantly different between the two dolichofacial subgroups (33.2 ± 6.8° vs 32.6 ± 3.7°) but SN-GoGn was significantly smaller ($P = .03$) for the brachyfacial group (29.8 ± 5.5°) compared to the two dolichofacial groups combined (33.0 ± 5.9°).

DISCUSSION

Mechanobehavior, the product of magnitude and frequency of jaw loading behaviors, influences TMJ growth and maintenance as well as degenerative changes, which generally occur earlier in the human TMJ than in other post-cranial joints.[10] Published data from sleep-lab[20] and at-home EMG[15,19,21] show that low-level jaw muscle activations associated with bite forces <5 N predominate during awake and sleep states. The combination of these low-level jaw muscle activities (duty factors), and the mechanical work input per disc volume during jaw functions (energy densities), produced the mechanobehavior scores (MBS). In the current study, MBS explained 57% and 81% of the mandibular ramus length variance (Co-Go) shown by females and males, respectively.

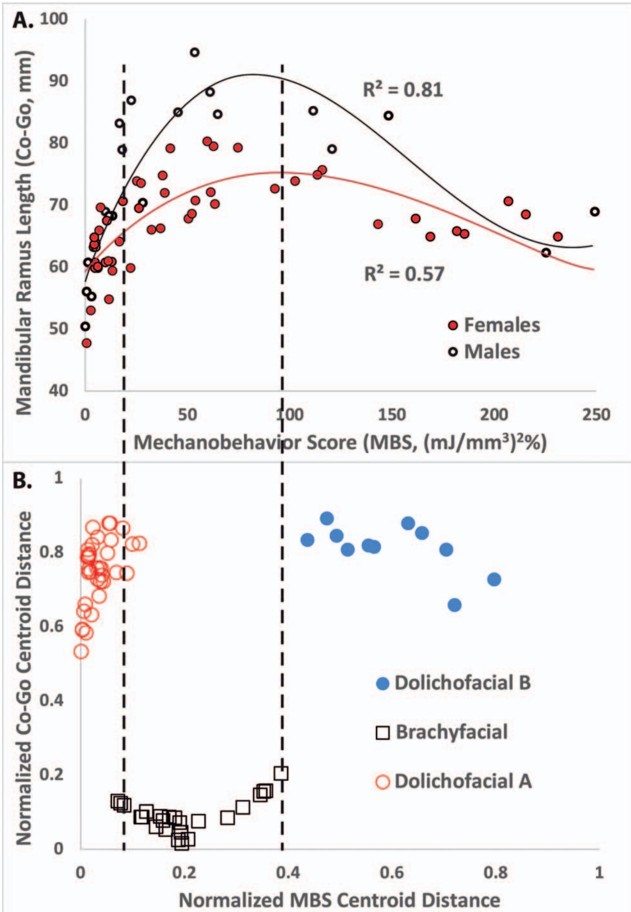

Figure 5. (A) Mandibular ramus length (Co-Go) vs mechanobehavior score (MBS, $(\frac{mJ}{mm^3})^2\%$) in females and males. (B) Cluster analysis showed normalized Co-Go vs MBS centroid distances segregated a group with brachyfacial features from two subgroups with dolichofacial features.

A scientific rationale for measuring mechanobehavior is that fibrocartilage stem cells in the TMJ perichondrium[12] have mechanosensitive genes (eg, IHH, SOST, FGF, TGFβ, WNT), which can influence growth, homeostasis, and senescence of the secondary cartilages.[13] If polymorphisms for mechanosensitive genes augment or diminish signal transduction, thereby modifying responsiveness of the TMJ secondary cartilages to mechanical stimuli, that is unknown. Also unknown is whether asymmetric differences in mechanosensitive genes, like those seen in asymmetric craniofacial anomalies,[22,23] affect unilateral differences in mechanosensitive genes in response to symmetric mechanobehavior.

Mandibular condyle growth can increase ramus length. Although hypothetical currently, if dolichofacial subgroups with high and low MBS also exist in growing children, early interventions to optimize mandibular condyle growth and, thus, optimize ramus length and jaw relationships may be possible and should be investigated in the future. As a theoretical example, in dolichofacial individuals with low MBS, increasing DF by prescribing a gum-chewing protocol, and thereby increasing the MBS into the optimal range, might be a simple means of improving outcomes of orthopedic treatment. Also theoretically, some individuals with high MBS may be expected to have poorer outcomes from orthopedic treatment as children and adolescents, and also be more prone to precocious development of degenerative TMJ changes as adults.[10] If the high MBS are due to relatively large DF then, theoretically, it may be possible to use biofeedback to attenuate DF during the day and improve orthopedic treatment results. Focusing on awake-state muscle activities may be more fruitful given that previous studies showed significantly larger DF during the awake state compared to sleep state,[24] and significantly larger TMJ ED during loaded asymmetric, compared to symmetric jaw movements.[17] If the high MBS are due to relatively large TMJ ED, dynamic stereometry could determine the ideal mandibular position for improved orthopedic appliance design. This ideal mandibular position would produce the best TMJ hard tissue surface matching and, thus, would minimize TMJ stress concentrations and ED.[10]

The current study's limitations included: adult subjects only, MBS based on symmetric jaw movements, unilateral ambulatory EMG recordings, imbalanced numbers of females and males, and incomplete data that excluded some subjects. Futures studies should investigate facial type differences in three-dimensional craniomandibular anatomy and effects on TMJ forces and should follow younger subjects with potential for jaw growth longitudinally to test if MBS can predict ramus length. In addition, MBS based on actual jaw behaviors of individual subjects may be possible via application of computing recognition algorithms to ambulatory EMG recordings for specific jaw behavior detection.[21]

CONCLUSIONS

- Mechanobehavior scores were correlated with ramus length in females and in males.
- Mechanobehavior scores were significantly different between subjects with brachyfacial features (longer ramus length, flatter mandibular plane angle) compared to two subgroups of subjects with dolichofacial features (shorter ramus length, steeper mandibular plane angle).
- Mechanobehavior scores were lower and higher in dolichofacial subgroups than the brachyfacial group.

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