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Research Article

Racial Variations in Velopharyngeal and Craniometric Morphology in Children: An Imaging Study

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Purpose: The purpose of this study is to examine craniometric and velopharyngeal anatomy among young children (4–8 years of age) with normal anatomy across Black and White racial groups.
Method: Thirty-two healthy children (16 White and 16 Black) with normal velopharyngeal anatomy participated and successfully completed the magnetic resonance imaging scans. Measurements included 11 craniofacial and 9 velopharyngeal measures.
Results: Two-way analysis of covariance was used to determine the effects of race and sex on velopharyngeal measures and all craniometric measures except head circumference. Head circumference was included as a covariate to control for overall cranial size. Sex did not have a significant effect on any of the craniometric measures. Significant racial differences were demonstrated for face height. A significant race effect was also observed for mean velar length, velar thickness, and velopharyngeal ratio.
Conclusion: The present study provides separate craniofacial and velopharyngeal values for young Black and White children. Data from this study can be used to examine morphological variations with respect to race and sex.

The velopharyngeal mechanism is a muscular valve that includes the velum, lateral pharyngeal walls, and posterior pharyngeal wall. Velopharyngeal function is accomplished through the combined action of several muscles including the levator veli palatini (levator), superior pharyngeal constrictor, musculus uvulae, palatoglossus, and palatopharyngeus (Seaver & Kuehn, 1980). The levator muscle is the primary muscle responsible for velar retraction and elevation. The muscle originates from the base of the skull and courses in a medial, inferior, and anterior direction to the insert into the body of the velum (Huang, Lee, & Rajendran, 1998; Moon & Kuehn, 2004). Studies have examined the velopharyngeal muscles using dissection (Barsoumian, Kuehn, Moon, & Canady, 1998; Mehendale, 2004), histology (Kuehn & Kahane, 1990), electromyography (Kuehn & Moon, 1994), and muscle biopsy during surgery (Lindman, Paulin, & Stål, 2001). However, these are invasive methods for assessing muscle tissue and function. Magnetic resonance imaging (MRI) has been demonstrated to be a useful tool for imaging the velopharyngeal structures because of its ability to visualize the muscles, in vivo (Ettema, Kuehn, Perlman, & Alperin, 2002). There are currently no other imaging techniques that allow for a three-dimensional (3-D) view of the velopharyngeal muscles in vivo.

Studies have demonstrated the use of MRI in assessing levator muscle characteristics in adults with normal velopharyngeal anatomy (Bae, Kuehn, Sutton, Conway, & Perry, 2011; Ettema et al., 2002; Perry, Kuehn, & Sutton, 2013) as well as in adults with repaired cleft palate and hypernasal speech (Ha, Kuehn, Cohen, & Alperin, 2007). Ha et al. (2007) reported that participants with residual hypernasality demonstrated levator muscle dimensions that were different from levator muscle features in adults without cleft palate. Perry, Kuehn, Sutton, Gamage, and Fang (2014) hypothesized that velopharyngeal structures vary on the basis of sex and race among the adult population with normal anatomy. Velopharyngeal anatomy and craniometric dimensions were assessed using a large sample size ($N = 89$) distributed across three adult populations (Black, White, and Asian). Palate height, linear cranial base, face height and width, and levator length were found to have significant sex differences, with men demonstrating larger values compared with women. Craniometric measures including face width, linear base values, cranial base angle, and velar measures (velar length and thickness) were found to vary significantly on the basis of race. The differences

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in mean levator muscle measures among three adult racial groups were not statistically significant; however, significant sex differences were noted across velopharyngeal muscles after removing the effect of the individual's head size. Race and sex were found to have a significant effect on velar length and thickness.

Studies using MRI in child populations have been slower to evolve due to decreased imaging speeds and difficulties in controlling motion artifacts. As such, MRI studies of the velopharyngeal anatomy among children with normal anatomy have been limited to small sample sizes (Kollara & Perry, 2014; Tian, Li, et al., 2010; Tian, Yin, Li, et al., 2010; Tian, Yin, Redett, et al., 2010). These studies have included White, Black, and Chinese child participants. However, no statistical analyses were conducted to examine velopharyngeal variations among different racial groups despite the significant racial differences found among adult participants (Perry et al., 2014). There is a dearth of research on the levator muscle variations among children from Black racial groups. No studies have addressed whether the race and sex differences reported by Perry et al. (2014) are consistent among the child population.

Research examining the effects of race and cranial morphology on velopharyngeal anatomy in children has been limited due to less advanced and slower imaging methods. In addition, methods have not evaluated a child-friendly protocol on a large child data set using behavioral and environmental modifications to limit motion artifacts. Research related to the anthropometric characteristics of the velopharyngeal mechanism in young children is important in providing insights that can guide our understanding of anatomic variations, such as in cleft palate anatomy. Anatomical data of the velopharyngeal mechanism in children are also valuable because this is the primary age group for determining secondary surgical needs related to velopharyngeal dysfunction.

Studies have emphasized the importance of understanding the racial and sex variations in the velopharyngeal anatomy (Chung & Kau, 1985; Chung, Runck, Bilben, & Kau, 1986; Perry et al., 2014). More specifically, studies have discussed the use of presurgical anatomy data to guide proper surgical treatment options among children born with cleft lip and palate (Inouye, Pelland, Lin, Borowitz, & Blemker, 2015). Finite element modeling of the velopharyngeal mechanism has provided support for presurgical planning that is guided by patient presurgical anatomy. Inouye et al. (2015) used computational modeling to demonstrate how variations in surgical maneuvers used in primary cleft palate repair can influence the outcome for proper muscle function. Inouye et al. (2015) further demonstrated how variations in presurgical anatomy influence the muscle function outcomes using a single surgical technique in cleft palate repair. Farkas, Katic, and Forrest (2007) highlighted the need for separate norms across different racial groups to guide and tailor craniofacial surgery. The paucity of normative 3-D data is a significant obstacle for surgical stimulation procedures (Altobelli et al., 1993). Perry et al. (2014) proposed that the racial and sex variations in velopharyngeal anatomy found among adults may indicate that a patient's race and sex are features that inform the surgical treatment decisions in cleft palate care. Investigations of race and sex variations, however, have been limited to adult populations.

The purpose of this study was to examine the craniometric and velopharyngeal anatomy among young children (4–8 years of age) with normal velopharyngeal anatomy across two racial groups: Black and White. This study aims to provide preliminary data to improve our understanding of the velopharynx and cranial anthropometry across two racial groups. Consistent with the comparable adult findings (Perry et al., 2014), it was hypothesized that race would have a significant effect on craniofacial and velar structures in children. Given that the cranium houses the internal musculature, the predictive ability of cranial features in determining orientation and morphology of the levator muscle was also assessed.

Method

Participants

In accordance with the approved Institutional Review Board proposal, 32 healthy children (16 White and 16 Black) were recruited. The participant group consisted of equal male and female groups by race, including 8 White boys, 8 White girls, 8 Black boys, and 8 Black girls. All participants self-reported the same ancestry (African American or European American) across three generations (i.e., both parents and all four grandparents having the same race). Self-report is considered the gold standard for racial classification (Kaufman & Cooper, 2001). Participants were between 4 and 8 years of age ($M = 6.06$, $SD = 1.4$), with a mean height of 46.4 in. ($SD = 5.0$) and a mean weight of 51.7 lbs. ($SD = 15.6$). Black participants were, on average, 12 months older and of greater height (5.2 in.) and weight (18.84 lbs.) compared with White participants. However, mean body mass index (BMI) between White and Black participant groups differed by an index of less than 1.5. Height ($p = .003$), weight ($p = .001$), and BMI ($p = .044$) were found to be significantly different for Black and White groups on the basis of paired t-test results. For these reasons, analyses of covariance (ANCOVA) were used, as described below in statistical analyses.

The typical age for determining secondary surgical requirements in a child with repaired cleft palate and residual hypernasality is between 4 and 8 years of age. This is also an important period for speech, language, and communication development. Nine years has been reported to be the onset time for significant growth in the thickness of midfacial tissue in Black children (Williamson, Nawrocki, & Rathbun, 2002). Hence, children between 4 and 8 years of age were selected to participate in the study. The demographics of the participants are presented in Table 1.

Participants were recruited through flyers placed in the community. Participants' parents reported no history of congenital syndromes, neurological disorders, craniofacial

Table 1. Subject demographics with means and standard deviations (in parentheses).

Subjects	*n*	Mean age (years) *M* (*SD*)	Mean weight (lbs.) *M* (*SD*)	Mean height (in.) *M* (*SD*)	Mean head circumference (mm) *M* (*SD*)	Mean Body Mass Index (BMI) *M* (*SD*)
White boys	8	5.54 (1.1)	42.09 (5.3)	44.07(4.6)	521.25 (20.3)	15.28 (1.50)
White girls	8	5.55 (1.5)	43.25 (9.8)	43.04 (3.6)	504.48 (11.5)	15.96 (1.69)
Black boys	8	6.32 (1.6)	67.10 (18.9)	49.06 (5.9)	517.05 (30.1)	17.71 (2.61)
Black girls	8	6.80 (1.1)	58.32 (16.7)	49.06 (4.3)	499.38 (26.1)	16.81 (2.02)

anomalies, musculoskeletal disorders, or swallowing disorders that could potentially affect the regions that were investigated for the study. No children had a history of tonsillectomy or adenoidectomy. The participants were all native English speakers. A speech-language pathologist administered an oral mechanism examination on all participants to assess the structural integrity of the articulators and to ensure that all participants had normal oral structures and function. In addition, a perceptual rating scale was used to evaluate nasality. All participants were formally rated by two speech-language pathologists (first and second authors) with experience in resonance using a 4-point scale (0 = *normal resonance*; 3 = *severe hypernasality*) and determined to have normal oral-to-nasal balance as indicated by a score of 0 on the rating scale. A perceptual evaluation was also conducted to rule out articulation errors for the targeted speech sounds for the study.

Prescan Training

All participants underwent training before starting the MRI exam. An established child-friendly protocol was used to familiarize the participants with the scanning process (Kollara & Perry, 2014). In brief, all participants were given MRI coloring sheets specifically designed for children to introduce them to the MRI study process. Participants were given the opportunity to explore the MRI machine with their parent and the investigator a few minutes before their respective MRI scans. Participants were encouraged to watch the participant being imaged before their assigned study time. To eliminate coercion, all participants were given time (5–10 min) to adapt to the new environment. The investigator proceeded with the study only if the participants were fully comfortable with the procedure. The parent was in the scanning room for the duration of the scan. The investigator communicated with the participants throughout the exam via a speaker-microphone system between the scanning and control rooms. The participants were frequently asked about their comfort level and were given a panic button. To minimize distractions, participants were allowed to listen to music during the duration of the scan. Small foam cushions were placed in the head coil on either side of the participant's head to minimize motion artifacts.

MRI

Participants were scanned using two different scanners with the same MRI protocol. All participants were imaged at rest in the supine position. MRIs were acquired on 19 participants using a 1.5 Tesla Philips Intera scanner (Philips, Eindhoven, Netherlands). A high resolution, T1-weighted turbo-spin-echo (TSE) 3-D anatomical scan called SENSE was utilized. The remaining 13 participants were imaged using a 3.0-Tesla General Electronics scanner. The protocol used for this scanner included a three-plane localizer, midsagittal T2-fluid attenuation inversion recovery (FLAIR), and coronal, oblique coronal, and axial fast spin echo (FSE) sequences. Scanning sequence protocols were designed to display similar image in-plane resolution using the same matrix (256 × 256), slice thickness (1.5 mm), spacing (0 mm), and pulse sequences (echo time = 17 ms; repetition time = 3,000 ms). This enabled comparisons between MRI data obtained across the two study sites.

Image Analyses

The MRI images were transferred into Amira 4 Visualization Volume Modeling software (Visage Imaging GmbH, Berlin, Germany). Amira has native Digital Imaging and Communication in Medicine (DICOM) support program that enables preservation of original geometry of the data.

Eleven craniofacial measures were obtained from the MRI data in the midsagittal and coronal image planes. A description and demonstration of each measure is provided in Table 2 and Figure 1. The craniofacial measures include head circumference, nasion to sella, sella to basion, basion to opisthion, nasion to basion, hard palate length, pharyngeal depth, nasion-sella-basion (NSB) angle, sella-basion-opisthion (SBO) angle, face height, and face width.

Nine velopharyngeal measures were obtained in the midsagittal and oblique coronal image planes. The oblique coronal plane that displays the levator muscle sling in its entirety was obtained by resampling the midsagittal image. These measures included levator muscle length, extravelar length, intravelar length, origin to origin, velar insertion, angles of origin, velar length, velar thickness, and velopharyngeal ratio (ratio of velar length to pharyngeal depth). The measures are described in Table 3 and demonstrated in Figures 1 and 2. The measurement procedures have been described previously (Kollara & Perry, 2014).

Statistical Analyses

Statistical analyses were conducted on 32 participants to determine racial and gender variations among the 11 craniometric and nine velopharyngeal measures and to

Table 2. Description of the 11 craniometric measures.

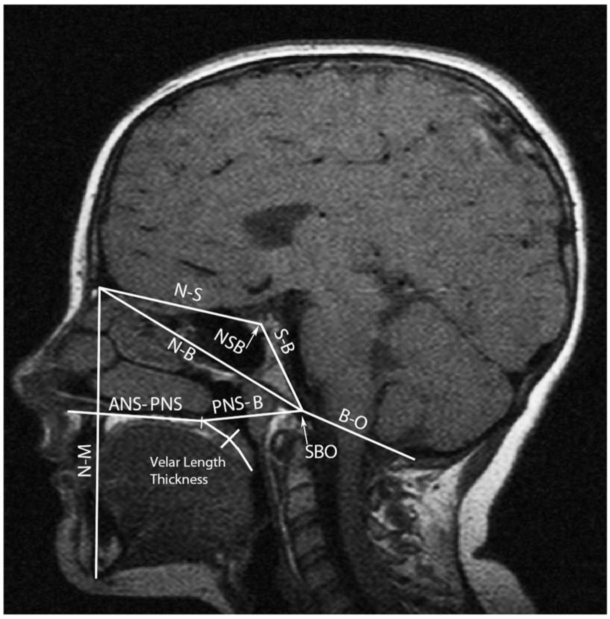
Measure	Definition
Head circumference	The maximal diameter of the head, measured around the frontal forehead and occiput, just above the brow line
Nasion to sella	Linear distance from nasion to sella
Sella to basion	Linear distance from sella to basion
Basion to opisthion	Linear distance from basion to opisthion
Nasion to basion	Linear distance from nasion to basion
Hard palate length	Distance from the anterior nasal spine (ANS) to the posterior nasal spine (PNS)
Pharyngeal depth	Distance from the PNS to the basion
NSB angle	Inner angle formed between two intersecting lines, one connecting the nasion to sella and the other connecting basion to sella
SBO angle	Inner angle formed between two intersecting lines, one connecting sella to basion and the other connecting opisthion to basion
Face height	Distance from nasion to menton
Face width	Distance between the most lateral portions of the zygomatic arches

Note. NSB = nasion-sella-basion; SBO = sella-basion-opisthion.

determine the associations between the variables. The assumption of normality was adequately met for all group combinations of race and gender, as assessed by formal tests (Shapiro-Wilks's test) and graphical representation (Q-Q plots). Homogeneity of variance was reasonably met for all combinations of race and gender as assessed by Levene's test of homogeneity of variance and graphical representation (scatterplot of residuals versus predicted values). A two-way ANCOVA was conducted to determine the relationship between race and sex and the means of the velopharyngeal and craniometric measures.

Statistical analysis revealed a significant correlation between head circumference and height ($r = .437$, $p = .012$) and weight ($r = .49$, $p = .004$). The correlation between height and weight was also noted to be significant and highly correlated ($r = .88$, $p = .000$). Because the variables of height, weight, and head circumference were correlated, it was determined that it would be redundant to use all three variables as covariates because they are all examining similar features related to overall size of the participant. During changes in body weight, head circumference remains as a valid and reliable measure regardless of the individual's overall size. Therefore, only the measure of head circumference was included as a covariate. In addition, this variable was used because it is the closest anatomic structure to the dependent variables that can be measured reliably and then used to remove the effect of differences in individual size between participants. We excluded individuals who were obese (having a BMI over 30) due to the known increased velar thickness due to fatty tissue around the velar body (Horner et al., 1989). In the present study, fat pads were not observed in nonobese individuals, despite their variations in height and weight. To determine how well craniometric measures could predict velopharyngeal muscle measures, multiple regression analyses were conducted. Given that the cranium serves as the muscle attachment, the analysis aimed to determine which fixed and bony craniofacial markers could best predict the arrangement and orientation of the respective soft muscle velopharyngeal measures. The Bonferroni method was used to adjust the significance level to account for multiple comparisons. The adjusted significance levels used were the significance level (.05) divided by 20 for the ANCOVA and divided by 8 for the regression analyses, because there were 20 ANCOVAs and 8 regression analyses conducted.

Figure 1. Craniometric measures obtained in the midsagittal plane. N = nasion; S = sella; B = basion; O = opisthion; NSB = nasion-sella-basion angle; SBO = sella-basion-opisthion angle; ANS = anterior nasal spine; PNS = posterior nasal spine; M = menton.



Intrarater and interrater reliability measures were established using the Pearson product–moment correlation ($\alpha = .05$). Both primary and secondary authors had experience in 3-D MRI data processing. Reliability measurements were performed by measuring all variables from 13 randomly selected participants 2 months after the first measurements were obtained. Intrarater and interrater reliability ranged from $r = .70$ to $r = .97$. Paired t tests

Table 3. Description of the nine velopharyngeal (VP) measures.

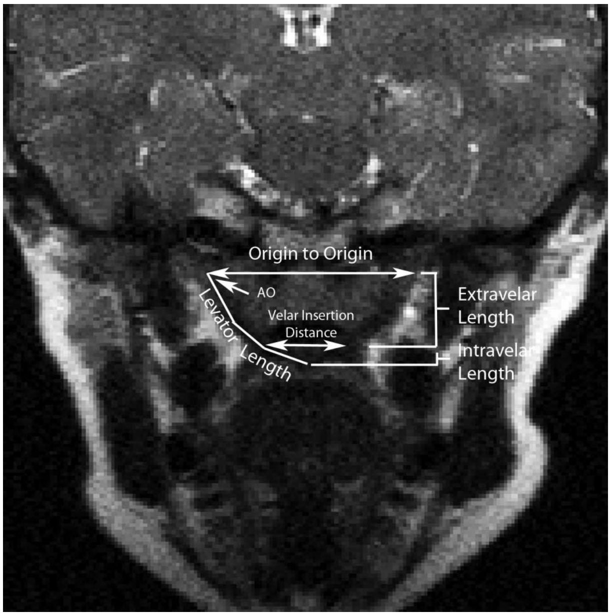
Measure	Definition
Levator length	Distance from the origin of the muscle at the base of the skull, through the middle of the muscle belly, and to the midline insertion at the velum
Extravelar length	Distance of the levator veli palatini muscle from its origin at the base of the skull to its insertion into the body of the velum
Intravelar length	Distance of the levator veli palatini muscle that is within the body of the velum
Origin to origin	Distance between the points of origin of the levator veli palatini muscle on the right and left sides
Velar insertion	Distance between where the levator veli palatini muscle inserts into the body of the velum on the right and left sides
Angles of origin	Angle created between a reference line connecting the two origins of the levator muscle and the line drawn to measure the levator muscle length
Velar length	Distance of a curvilinear line starting at the posterior nasal spine, coursing through the middle of the cross-sectioned velum, to the tip of the uvula
Velar thickness	Distance from the velar knee to the velar dimple
VP ratio	Velar length/pharyngeal depth

were conducted to determine intrarater and interrater differences. There were no statistically significant differences ($p > .05$) between the first and second measures by the first author. For intrarater reliability, the mean differences for the measures ranged from .02 to 1 mm. There were also no statistically significant differences ($p > .05$) between the measures from the two authors. The mean differences for the measures ranged from .05 to 1.2 mm across raters.

Results

Magnetic resonance images were obtained on all participants with a 100% success rate. Group estimated marginal means for craniometric and velopharyngeal measures (differentiated by race and gender) are reported in Tables 4 and 5. A two-way ANCOVA was used to determine the effects of race and sex on velopharyngeal measures and all craniometric measures except head circumference (see Tables 6 and 7).

Figure 2. Oblique coronal image demonstrating levator muscle. AO = angle of origin.



Effects of Sex and Race on Craniometric Measures

Except in the case of head circumference, subsequent sections of this article report the effects after removing the effects of the covariate of cranial size (see Tables 6 and 7). Sex did not have a significant effect on any of the craniometric measures at the adjusted significance level of .0025 (see Table 6). A significant racial effect was evident only for face height, $F(1, 27) = 23.99$, $p < .0005$. Black participants had a significantly greater mean value for face height ($p < .0025$; 11% increase) compared with White participants, as determined by the estimated marginal means. A small-to-moderate effect size (.47) was observed for face height.

Effects of Sex and Race on Velopharyngeal Measures

Sex did not have a significant effect on any of the velopharyngeal measures at the adjusted significance level of .0025 (see Table 7). The extravelar segment of the levator muscle was found to be the same in boys and girls ($M = 24.8$ mm) after removing the effect of head circumference. The levator muscle measures did not demonstrate a statistically significant effect for race ($p > .0025$). However, significant ($p < .0005$) racial differences were observed for mean velar length, $F(1, 27) = 28.3$, $p < .0005$, and thickness, $F(1, 27) = 55.4$, $p < .0005$. Black participants demonstrated a significantly longer (38% longer) and thicker (40% larger) velum compared with White participants after adjusting for head circumference. There were no significant interaction effects of sex and race on the muscle measures. There was a significant racial effect for velopharyngeal ratio ($p < .0005$), with Black participants demonstrating a larger ratio than White participants. Analyses showed a moderate-to-large effect size for velar length (.51) and thickness (.67). A small-to-moderate effect size was noted for velopharyngeal ratio (.49).

Table 4. Estimated (adjusted for head circumference) marginal means and standard deviations (in parentheses) for each craniometric measures.

	White			Black			Combined *M*	
Measures	**Boy**	**Girl**	***M***	**Boy**	**Girl**	***M***	**Boy**	**Girl**
Head circumference	521.2 (7.9)	504.4 (7.9)	512.8 (5.5)	517.5 (7.9)	498.1 (5.5)	507.8 (5.5)	519.3 (5.5)	501.3 (5.5)
Nasion–sella	55.0 (1.4)	55.5 (1.4)	55.3 (1.0)	56.0 (1.4)	52.3 (1.5)	54.1 (1.0)	55.5 (1.0)	53.9 (1.0)
Sella–basion	32.8 (0.7)	32.8 (0.7)	32.8 (0.5)	35.0 (0.7)	35.1 (0.8)	35.1 (0.5)	33.9 (0.5)	34 (0.5)
Basion–opisthion	38.7 (1.3)	39.0 (1.3)	38.9 (0.9)	36.0 (1.3)	39.0 (1.4)	37.5 (0.9)	37.3 (1.0)	39.0 (1.0)
Nasion–basion	80.1 (1.4)	80.5 (1.3)	80.3 (0.9)	82.4 (1.3)	80.03 (1.4)	81.2 (0.9)	81.2 (1.0)	80.2 (1.0)
Hard palate length	42.9 (2.4)	45.8 (2.3)	44.4 (1.6)	40.9 (2.3)	43.56 (2.4)	42.2 (1.6)	41.9 (1.7)	44.6 (1.7)
Pharyngeal depth	39.2 (1.4)	39.5 (1.3)	39.3 (0.9)	44.6 (1.3)	41.9 (1.4)	43.3 (0.9)	41.9 (1.0)	40.7 (1.0)
NSB angle	130.9 (2.7)	129.8 (2.6)	130.3 (1.8)	131.6 (2.6)	132.2 (2.7)	131.9 (1.8)	131.3 (1.9)	131.0 (1.9)
SBO angle	224.3 (3.0)	222.4 (2.9)	223.3 (2.0)	222.5 (2.9)	228.0 (3.0)	225.3 (2.0)	223.4 (2.1)	225.2 (2.1)
Face height	86.1 (1.9)	88.8 (1.9)	87.5 (1.3)	97.4 (1.9)	96.3 (1.9)	96.9 (1.3)	91.8 (1.4)	92.6 (1.4)
Face width	110.4 (2.3)	115.5 (2.2)	112.9 (1.6)	113.8 (2.2)	109.2 (2.3)	111.5 (1.6)	112.1 (1.6)	112.4 (1.6)

Note. Values are noted in millimeters, with the exception of the angle measures (in degrees). NSB = nasion-sella-basion; SBO = sella-basion-opisthion.

Craniometric and Muscle Prediction Models

Multiple linear regression models were used to determine whether craniometric measures could predict the levator muscle and velar configurations and shapes (see Table 8). It was hypothesized that cranial features could predict levator muscle morphology and orientation given that the cranial base serves as the point of attachment of the levator muscle. Because some of the craniometric measures are strongly correlated, backward selection was used to obtain reduced regression models with fewer predictors. Four of the eight resulting models had significant predictive power (at an adjusted significance level of $p < .00625$). These muscle measures include velar length ($R^2 = .802$), velar thickness ($R^2 = .571$), levator length ($R^2 = .527$), and extravelar length ($R^2 = .382$).The three predictor model (hard palate length, PNS to basion, and NSB angle) was able to account for 80.2% of the variability in the length of the velum, representing a strong model. The predictive model for extravelar length (hard palate length) could only account for 38.2% of the variability for this muscle measure, indicating a weak model. Hard palate length appeared to be the most common significant craniometric predictor, being present in two muscle prediction models, which included extravelar length and velar length.

Multiple regression analyses were rerun for those muscle measures that demonstrated a statistically significant difference for race (on the basis of ANCOVA results). The final regression models are demonstrated in Table 8. These muscle measures included velar length and thickness. Race was included as a predictor in the regression models for both velar length and thickness. In the case of velar length, the R^2 increased to .827 and the nasion to basion predictor was replaced by race. Significant differences were observed in the regression model for velar thickness. With race included as an independent variable with the craniometric predictors, the regression model revealed that race was the only significant predictor for velar thickness ($p < .0005$). The R^2 value increased from .571 to .741. Thus, the regression model with just race as the predictor explains 74.1% of the variability in velar thickness.

Qualitative Differences

MRI scans demonstrating velopharyngeal anatomy in the midsagittal image plane are demonstrated in Figure 3. The top three images represent MRI data on Black participants, and the bottom three images represent data on White participants. The most significant qualitative difference is a longer and thicker velum for the Black participants

Table 5. Estimated (adjusted for head circumference) marginal means and standard deviations (in parentheses) for each muscle measures.

	White			Black			Combined *M*	
Measures	**Boy**	**Girl**	***M***	**Boy**	**Girl**	***M***	**Boy**	**Girl**
Levator length	33.6 (0.9)	32.9 (0.8)	33.2 (0.6)	35.8 (0.8)	34.2 (0.9)	35.0 (0.6)	34.7 (0.6)	33.5 (0.6)
Extravelar length	23.6 (0.9)	24.2 (0.9)	23.9 (0.6)	25.9 (0.9)	25.5 (0.9)	25.7 (0.6)	24.8 (0.6)	24.8 (0.6)
Intravelar length	17.9 (1.5)	17.4 (1.5)	17.7 (1.0)	19.9 (1.5)	18.2 (1.5)	19.0 (1.0)	18.9 (1.1)	17.8 (1.1)
Origin–origin	49.1 (1.5)	46.7 (1.4)	47.9 (1.0)	50.5 (1.4)	47.7 (1.5)	49.1 (1.0)	49.8 (1.0)	47.3 (1.0)
Velar insertion distance	18.5 (0.9)	16.3 (0.9)	17.4 (0.6)	18.4 (0.9)	16.3 (0.9)	17.4 (0.6)	18.5 (0.6)	16.3 (0.6)
Angle of origin	56.8 (1.7)	57.8 (1.6)	57.3 (1.1)	55.4 (1.6)	55.7 (1.7)	55.5 (1.1)	56.1 (1.2)	56.7 (1.2)
Velar length	21.8 (1.6)	23.1 (1.6)	22.4 (1.1)	30.3 (1.6)	31.7 (1.6)	31.0 (1.1)	26.0 (1.1)	27.4 (1.1)
Velar thickness	6.1 (0.3)	6.5 (0.3)	6.3 (0.2)	8.8 (0.3)	8.8 (0.3)	8.8 (0.2)	7.4 (0.2)	7.7 (0.2)
VP ratio	0.58 (0.07)	0.57 (0.04)	0.57 (0.05)	0.68 (0.11)	0.73 (0.07)	0.70 (0.09)	0.63 (0.10)	0.65 (0.09)

Note. Values are noted in millimeters, except for the angle measure (in degrees). VP = velopharyngeal.

Table 6. Results from the ANCOVA models, analyzing the effects of sex and race on craniometric measures.

Measures	Sex	Race	Interaction (sex & race)
Head circumference	$F(1, 28) = 5.217$ $p = .030$ (.15)	$F(1, 28) = .408$ $p = .528$ (.01)	$F(1, 28) = .027$ $p = .160$ (.00)
Nasion to sella	$F(1, 27) = 1.074$ $p = .309$ (.03)	$F(1, 27) = .621$ $p = .437$ (.02)	$F(1, 27) = 2.086$ $p = .528$ (.07)
Sella to basion	$F(1, 27) = .001$ $p = .970$ (.00)	$F(1, 27) = 8.460$ $p = .007$ (.23)	$F(1, 27) = .007$ $p = .936$ (.00)
Basion to opisthion	$F(1, 27) = 1.304$ $p = .263$ (.04)	$F(1, 27) = 1.056$ $p = .313$ (.03)	$F(1, 27) = 1.031$ $p = .319$ (.03)
Nasion to basion	$F(1, 27) = 0.456$ $p = .505$ (.01)	$F(1, 27) = .433$ $p = .516$ (.01)	$F(1, 27) = 1.105$ $p = .303$ (.03)
Hard palate length	$F(1, 27) = 1.142$ $p = .295$ (.00)	$F(1, 27) = .836$ $p = .369$ (.22)	$F(1, 27) = .002$ $p = .966$ (.05)
Pharyngeal depth	$F(1, 27) = .647$ $p = .428$ (.02)	$F(1, 27) = 8.337$ $p = .008$ (.23)	$F(1, 27) = 1.255$ $p = .272$ (.04)
NSB angle	$F(1, 27) = .008$ $p = .929$ (.00)	$F(1, 27) = .348$ $p = .560$ (.01)	$F(1, 27) = 0.097$ $p = .758$ (.00)
SBO angle	$F(1, 27) = .311$ $p = .582$ (.01)	$F(1, 27) = .427$ $p = .519$ (.01)	$F(1, 27) = 1.591$ $p = .218$ (.05)
Face height	$F(1, 27) = .146$ $p = .706$ (.00)	$F(1, 27) = 23.993$ **$p < .0005^*$ (.47)**	$F(1, 27) = .956$ $p = .337$ (.03)
Face width	$F(1, 27) = .014$ $p = .905$ (.00)	$F(1, 27) = .386$ $p = .540$ (.01)	$F(1, 27) = 4.605$ $p = .041$ (.14)

Note. Except for head circumference, test statistics represent the effect after adjusting for head circumference. The eta-squared value (in parentheses) demonstrates the effect size for the data. Statistically significant results shown in bold font.

$^*p < .05/20 = .0025$.

compared with that for the White participants. This finding is consistent with the quantitative findings from the present study. Consistent with the quantitative findings, no qualitative differences were observed for images in the oblique coronal image plane. All participants displayed a cohesive levator muscle sling with no separation of the levator muscle bundles from the velar midline (see Figure 4).

Discussion

The purpose of this study was to assess craniometric and velopharyngeal anatomy in young Black and White children using MRI. MRI scans were successfully obtained on all 32 children using a child-friendly scanning protocol with a 100% success rate. Vannest et al. (2014) investigated

Table 7. Results from the analysis of covariance (ANCOVA) models, analyzing the effects of sex and race on muscle measures.

Measures	Sex	Race	Interaction (Sex × Race)
Levator length	$F(1, 27) = 1.491$ $p = .233$ (.05)	$F(1, 27) = 3.996$ $p = .056$ (.12)	$F(1, 27) = 0.256$ $p = .617$ (.00)
Extravelar length	$F(1, 27) = 0.002$ $p = .963$ (.00)	$F(1, 27) = 3.677$ $p = .066$ (.12)	$F(1, 27) = 0.267$ $p = .610$ (.01)
Intravelar length	$F(1, 27) = 0.439$ $p = .513$ (.01)	$F(1, 27) = 0.792$ $p = .381$ (.02)	$F(1, 27) = 0.173$ $p = .681$ (.006)
Velar insertion distance	$F(1, 27) = 4.873$ $p = .036$ (.15)	$F(1, 27) = 0.002$ $p = .968$ (.00)	$F(1, 27) = 0.006$ $p = .938$ (.00)
Origin–origin	$F(1, 27) = 2.605$ $p = .118$ (.08)	$F(1, 27) = 0.699$ $p = .411$ (.02)	$F(1, 27) = 0.015$ $p = .902$ (.00)
Angle of origin	$F(1, 27) = 0.119$ $p = .733$ (.00)	$F(1, 27) = 1.166$ $p = .290$ (.04)	$F(1, 27) = 0.039$ $p = .846$ (.00)
Velar length	$F(1, 27) = 0.599$ $p = .446$ (.02)	$F(1, 27) = 28.386$ **$p < .0005^*$ (.51)**	$F(1, 27) = 0.003$ $p = .960$ (.00)
Velar thickness	$F(1, 27) = 0.375$ $p = .545$ (.01)	$F(1, 27) = 55.400$ **$p < .0005^*$ (.67)**	$F(1, 27) = 0.379$ $p = .543$ (.01)
VP ratio	$F(1, 27) = 3.610$ $p = .068$ (.11)	$F(1, 27) = 26.580$ **$p < .0005^*$ (.49)**	$F(1, 27) = 1.156$ $p = .292$ (.041)

Note. Test statistics represent the effect after adjusting for head circumference. The eta-squared value (in parentheses) demonstrates the effect size for the data. Statistically significant results shown in bold font.

$^*p < .05/20 = .0025$.

Table 8. Results from the multiple linear regression analyses.

Dependent variable	Regression equation	R^2	Predictor (and abbreviation)	*p* value for IV
Levator length	$\hat{y} = -104.455 + 0.076(\mathrm{HC}) + 1.825(\mathrm{NS}) + 1.557(\mathrm{SB}) - 1.810(\mathrm{NB}) + 0.711(\mathrm{NSB})$	.527	Head circumference (HC)	**.004***
			Nasion to sella (NS)	**.002***
			Sella to basion (SB)	**.003***
			Nasion to basion (NB)	**.004***
			NSB angle (NSB)	**.002***
Extravelar length	$\hat{y} = -9.696 + 0.043(\mathrm{HC}) + 0.368(\mathrm{HP})$	.382	Head circumference (HC)	.025
			Hard palate length (HP)	**.003***
Origin–origin	$\hat{y} = -99.821 + .109(\mathrm{HC}) + 2.196(\mathrm{NS}) - 2.439(\mathrm{NB}) + 0.460(\mathrm{HP}) + 0.774(\mathrm{NSB})$	.484	Head circumference (HC)	.009
			Nasion to sella (NS)	.019
			Nasion to basion (NB)	.017
			Hard palate length (HP)	.028
			NSB angle (NSB)	.031
Velar insertion	$\hat{y} = -42.246 + 1.468(\mathrm{NS}) + 1.310(\mathrm{SB}) - 1.552(\mathrm{NB}) + 0.459(\mathrm{NSB})$	.248	Nasion to sella (NS)	.014
			Sella to basion (SB)	.017
			Nasion to basion (NB)	.016
			NSB angle (NSB)	.035
Velar length	$\hat{y} = -4.151 + 0.535(\mathrm{HP}) + 0.814(\mathrm{PNS}) - 0.174(\mathrm{NSB}) + 3.716(\mathrm{race})$	.827	Hard palate length (HP)	**.002***
			PNS to basion (PNSB)	**.000***
			NSB angle (NSB)	.009
			Race	**.005***
Velar thickness	$\hat{y} = 3.869 + 2.208(\mathrm{race})$	.741	Race	**.000***

Note. R^2 value represents the proportion of variation in the dependent variable accounted for by the regression model. The regression equation represents the predictive model. IV = independent variable. Coding for race: 0 = White, 1 = Black. Statistically significant results shown in bold font.

$^*p < .05/8 = .00625$.

Figure 3. Magnetic resonance images demonstrating qualitative differences in velar length and thickness across different racial groups in the midsagittal plane. Top row (left to right): 7-year-old boy; 6-year-old girl; 5-year-old boy. Bottom row (left to right): 7-year-old girl; 4-year-old girl; 5-year-old boy.

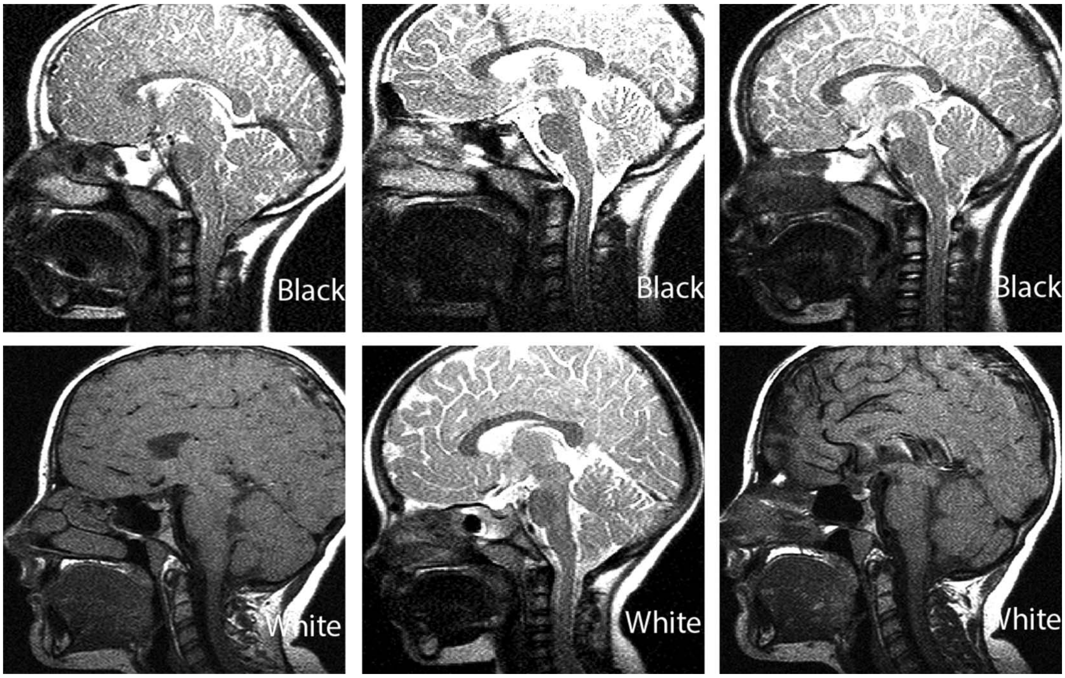
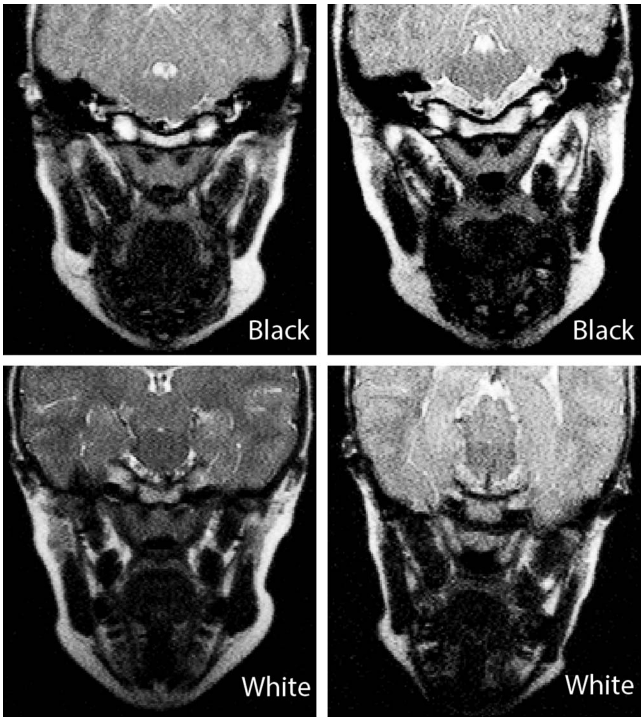


Figure 4. Magnetic resonance images demonstrating cohesive levator muscle sling in the oblique coronal plane.



the feasibility of successful completion of MRI scans in 158 children between the ages of 2.5 and 18 years without the use of sedation as part of a large-scale neuroimaging research protocol. Two scan sessions were assessed per participant. The success rates for each session were 0.739 and 0.847 for children aged 2.5 to 6 years. The success rates were higher (over 0.900 for both participants) for children 7 years and older. Results from the present study demonstrate the feasibility and application of our MRI methodology in providing qualitative and quantitative data on craniometric and velopharyngeal structures in young children as young as 4 years, without the use of sedation.

MRI studies in children present with difficulties such as motion artifacts and behavioral constraints. As such, there is limited literature on craniometric and velopharyngeal structures among children across different racial groups without the use of sedation. Sedation adds significant cost as well as additional risks such as negative effects of anesthesia or sedation medication and suppression of normal breathing (Halliday & Kelleher, 2013).The use of a laryngeal airway mask during sedation may also distort the positioning of oral structures and the velum at rest, which would be disadvantageous for any studies aimed at assessing velopharyngeal structural differences.

MRI studies of the velopharyngeal anatomy for this population have been limited to small sample sizes (Kollara & Perry, 2014; Tian, Li, et al., 2010; Tian, Yin, Li, et al., 2010; Tian, Yin, Redett, et al., 2010). The present study improves on current literature by adding to the craniofacial database on children, especially providing insight into the underrepresented Black child population. To our knowledge, this is the first study to demonstrate craniometric and velopharyngeal differences as a function of race in Black children between 4 and 8 years of age.

Findings from the present study demonstrate that craniometric measures did not vary significantly on the basis of sex and that only one craniometric predictor (face height) varied significantly on the basis of race. Studies have indicated that sexual dimorphism in children is evident closer to 14 years of age for most skeletal cranial structures (Ursi, Trotman, McNamara, & Behrents, 1993). Consistent with previous reports, there were no differences on the basis of sex for the measures of sella to basion and NSB angle across participants (Lewis & Roche, 1977; Ursi et al., 1993). Significant sexual dimorphism for the measure of nasion to sella was not observed as reported by Ursi et al. (1993). Anthropometric measures in the horizontal dimension, such as facial width, have been reported to differ significantly between older adult Black and White girls, with Black girls demonstrating greater facial width compared with White girls (Porter & Olson, 2001). No such significant race effects in the horizontal dimension were indicated in our data for the younger child population. The discrepant findings between children and adults regarding face width may be due to the effects of pubertal changes on craniofacial characteristics.

Findings in the younger population in the present study are not consistent with variations reported in the adult population (Perry et al., 2014). The cranial measures of nasion to sella (Japanese < Black < White), sella to basion (Black < White < Japanese), NSB angle (White/Japanese < Black), and face width (White < Japanese/Black) were found to vary significantly in adults on the basis of race (Perry et al., 2014). In the present study, it was found that only facial height differed across the racial groups of Black and White. It has been established that there is a strong pubertal effect for cranial measures (Roche & Lewis, 1974; Ursi et al., 1993). It is likely that data in the present study demonstrate a prepubertal effect of growth on skeletal and soft tissue measures in which differences seen in adults are not consistent with those among the prepubertal child population. Further studies should investigate the effects of sex and race differences as a function of pre- and post-pubertal growth changes. Contradictory findings on craniometric and velopharyngeal anatomy in adult and child populations further highlight the need for longitudinal data across the lifespan on relevant craniometric and velopharyngeal measurements.

A consistent trend was observed for the measures of sella to basion, pharyngeal depth, and anterior cranial base angle (NSB angle), with Black participants having larger values for all three measures, thus contributing to a larger pharyngeal dimension. Black participants also demonstrated significantly greater face height values. In a similar study on adults (Perry et al., 2014), it was hypothesized that although Black participants showed greater anterior-to-posterior distances, the increased length and thickness of the velum would counteract any differences in the velopharyngeal port dimensions. The authors, however, did not report objective measures regarding the velopharyngeal port ratio. In the present study, it was also thought that the increased length and thickness demonstrated by these participants would counteract any effects of race on the dimensions of the velopharyngeal port, as measured by the velopharyngeal ratio. However, a statistically significant racial effect was observed for this measure, which could be due to the prepubertal growth effects on the skeletal and pharyngeal morphology. Anthropometric studies have suggested that anatomic variations may predispose certain racial groups to clefting (Chung & Kau, 1985). Chung and Kau (1985) hypothesized that clefting may be related to these morphological cranial variations, which in turn could be related to inherent craniofacial variations on the basis of race. Current research aims to identify the relationship of genetics to cleft markers (Lidral & Moreno, 2005; Vieira et al., 2015). However, to our knowledge, no studies have investigated gene association related to clefting across different racial groups.

Velopharyngeal measures are consistent with data reported by previous studies (Kollara & Perry, 2014). Kollara and Perry (2014) reported data on similar velopharyngeal measures (velar length, velar thickness, levator length, and angles of origin); however, data were not separated by race or sex. In a similar study on adults (Perry et al., 2014), it was found that adult men demonstrated significantly longer extravelar and intravelar muscle segments compared with women. However, in the present study, it was noted that boys and girls presented with the same extravelar length in this age group ($M = 24.8$ mm), after removing the effects of cranial size. As such, there were no significant effects of sex on any of the velopharyngeal measures among the young child population. The effects of growth on the levator muscle measures warrant further investigation. Consistent with reported findings in adult participants (Perry et al., 2014), Black participants were observed to have a significantly longer and thicker velum in comparison to White participants. Future studies investigating similar velar variables may thus need to control for race but not sex.

The levator muscle origin is bound by craniofacial structures, and we anticipated that variations in skeletal craniofacial structures may affect the positioning of the levator muscle. As such, it was hypothesized that regression models could predict soft muscle measures from hard tissue (craniometric) structures. Predictive models with high R^2 values were, however, only present for velar length and thickness. There are no significant predictive models for the levator muscle measures. Hard palate length was observed to be the more common craniometric predictor, as it was present in two muscle prediction models—extravelar length and velar length. The multiple linear regression analyses demonstrated in the present study may serve as a preliminary indicator of the potential utility of craniometric markers in assessing muscle morphology in clinical populations. It may be particularly relevant in clinically challenging populations such as in individuals with 22q11.2 deletion syndrome, where abnormal craniofacial and velopharyngeal characteristics are exhibited, but the relationship or effect that one may have on the other is not well understood. For example, studies have documented variations in hard palate length, cranial base angle, and velar length among this clinical population (Arvystas & Shprintzen, 1984; Heliovaara & Hurmerinta 2006; Ruotolo et al., 2006). Punjabi, Holshouser, D'Antonio, and Kuehn (2002) observed individuals with 22q11.2 deletion syndrome to have an abnormal levator muscle characterized as being thin and hypoplastic. However, no studies have determined if the abnormal levator muscle variables are correlated to abnormal cranial base values or if a shorter hard palate could result in a shorter velum. Further studies should investigate how prediction models can be incorporated into modeling and analysis of the biomechanics of the velopharyngeal port.

It has been established that understanding normal anatomy is necessary in evaluating and determining dysmorphic anatomy (Perry et al., 2013). As such, there is a need for continued research regarding the anatomy and function of the velopharyngeal mechanism. Recent work on computational modeling (Inouye et al., 2015) has discussed the potential of using normal anatomical data to systematically investigate in vivo function of the velopharyngeal mechanism. The computational model in that study was built using MRI data from previously reported investigations and was used to determine how surgical parameters could be altered using patient presurgical anatomy. Data from this study may add to the normative velopharyngeal and craniofacial database for children.

Limitations of the Present Study

Limitations of the present study include a small sample size and the inclusion of only two racial groups (Black and White). Height and weight were not included as covariates (in addition to head circumference) due to the small sample size and the correlation among variables of height, weight, and head circumference. Horner et al. (1989) demonstrated obesity (BMI greater than 30) is associated with fatty tissue around the velum. Adult control participants who were not obese, yet showed variations in weight, did not display differences in velar thickness. No participants in the present study were classified as obese. However, studies have not demonstrated whether weight or height is correlated to any velar or pharyngeal measures among the child population. Another limitation of the study is the lack of muscle activity data during speech tasks. A limitation of these anatomical structural data is the lack of functional variations of the velopharyngeal musculature. Our laboratory is currently investigating the functional variations among child populations using dynamic MRI.

Conclusion

The MRI methodology detailed in this study describes an effective means to assess craniofacial and velopharyngeal characteristics in young children without the use of sedation. Future investigations may adopt the behavioral protocol outlined in this study across larger study groups and for clinically challenging populations such as children with 22q11.2 deletion syndrome. The present study provides separate craniofacial and velopharyngeal values for young Black and White children. Although there was no significant race effect on the levator muscle, significant racial variations were noted for velar length and thickness. The paucity of normative 3-D data is an obstacle for surgical stimulation procedures (Altobelli et al., 1993). Data from this study will add to the growing database of craniometric and velopharyngeal measurements for use in 3-D reconstruction and modeling, and can be used to examine morphological variations with respect to race and sex.

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