Relational growth of oral and pharyngeal structures with vocal-tract length during the first two decades of life as visualized from MRI and CT studies

Houri K. Vorperian[a], Shubing Wang[b], Moo K. Chung[b], Reid B. Durtschi[a], E. Michael Schimek[a], Lindell R. Gentry[c] & Ray D. Kent[a]

[a] Waisman Center, [b] Departments of Statistics, Biostatistics & Medical Informatics, [c] Department of Radiology
University of Wisconsin - Madison

Waisman Center

ASHA Convention- Chicago, IL
Session # 1838; Poster 244
21 November 2008

ABSTRACT
Variability in acoustic and physiologic measures of speech production decreases as age increases. This has been attributed to neural maturation of speech motor control. However, the role of anatomic growth of the speech production system on variability needs to be examined. In this study, quantitative measurements of the various soft tissue, cartilaginous and bony vocal tract (VT) structures in the oral and pharyngeal regions were secured from 645 imaging studies (MRI & CT; ages birth to 19 years). These measurements were then used to assess the relational growth of these various VT structures with vocal tract length (VTL) using r-squared curves. Results show differences in the relational growth of oral and pharyngeal structures with VTL including sex-specific prepubertal and pubertal differences. An important implication is the need to incorporate developmental anatomy information in the understanding of speech motor control development.

INTRODUCTION
The human supralaryngeal speech apparatus undergoes drastic anatomic growth and restructuring particularly during the first few years of life. The development of multiple oral and pharyngeal structures contribute towards vocal tract lengthening, which increases more than twofold from infancy to adulthood. Such anatomic developmental changes, which have been characterized to be nonlinear and non-uniform [4, 5, 8, 19], provide part of the biological foundation for speech emergence and development [2, 9, 15]. Advancements in imaging technology (CT & MRI) have facilitated the quantification of the developing vocal tract (VT) anatomy and its individual bony and soft tissue structures [1, 6, 17, 18].

Acoustic theory asserts a relationship between the anatomy of the developing VT and the spectrum shape of speech sounds observed during development [4]. Thus, ultimately, knowledge on anatomic growth of VT structures needs to be incorporated into theoretical constructs on motor speech development in children. The increased variability that has been noted in acoustic and physiologic measures of speech production in children, which reportedly decreases by about age 10 -12, has been attributed to neural maturation [10, 14]. However, concurrent to neural maturation there is anatomic growth where various structures display different growth patterns with sex-specific growth rates [19]. Thus, it is reasonable to hypothesize an increased predisposition to a breakdown, or increased variability, when two or more structures that perform the function of speech do not exhibit coordinated growth. Assessing variability with detailed knowledge of anatomic growth patterns is necessary to understand anatomic versus neural contributions to speech development.

The **specific purpose** of this study is to assess anatomic developmental changes in the relational growth of VT structures in the oral and pharyngeal regions with vocal tract length (VTL) for both sexes during approximately the first two decades of life. Also, to examine similarities and differences in the relational growth of the different VT structures to assess concurrent or coordinated growth.

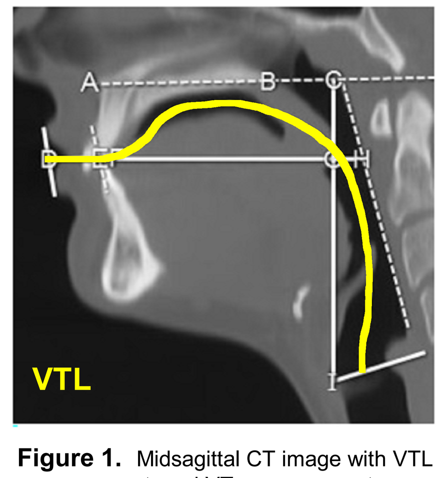


Figure 1. Midsagittal CT image with VTL measurement and VT measurement landmarks.

METHODS AND PROCEDURES
Subjects: A total of 645 head and neck imaging studies (MRI & CT; 351 males & 294 females) ages birth to 20 years are included in this study.

Image Acquisition and Data Acquisition: Methods same as specified in Vorperian et al. (*2005*). Measurements of bony and soft tissue structures in the oral and pharyngeal regions of the VT, as defined below, were made after the placement of all landmarks. The use of landmark placement protocol improved measurement accuracy between 82 and 100 % (average 98%) as measured by reduction in error variability 3.

Measurement Definitions:
Structures in the **oral region** of the VT in the **horizontal plane** are highlighted in **yellow** in figures 2 to 7.
Structures in the **pharyngeal region** of the VT in the **vertical plane** are highlighted in **green** in figures 2 to 7.

1. **Vocal Tract Length (VTL):** The curvilinear distance along the midline of the tract starting at the glottis to the intersection with a line drawn tangentially to the lips. See Figure 1.
2. **Vocal Tract-Horizontal (VT-H):** The horizontal distance from a line tangential to lips to the posterior pharyngeal wall. Distance D-to-H in Figure 2.
3. **Vocal Tract-Vertical (VT-V) :** The vertical distance from the glottis to the palatal plane (A-to-B plane). Distance I-to-C in Figure 2.
4. **Lip Thickness (LTh):** The distance, at the level of the stomion, between two lines, the first of which is drawn tangential to the anterior aspect, and the second to the posterior or buccal aspect of the maxillary and mandibular lips. Distance D-to-E in Figure 3.
5. **Hard palate length (HP):** The curvilinear distance along the hard palate contour from the anterior point of the incisor or tooth bud to the beginning of the soft palate. See Figure 4.
6. **Soft palate length (SP):** The curvilinear distance from the posterior edge of the hard palate to the inferior edge of the uvula. See Figure 4.
7. **Tongue Length:** The curvilinear distance along the dorsal superior contour of the tongue from the tongue tip to the valleculae. The hard/soft palate junction was used to divide the tongue into an anterior (**Tong-Ant**) versus posterior segments (**Tong-Post**).
8. **Mandibular length and depth:** The horizontal and vertical distances in the midsagittal plane from the mental protuberance to the orthogonal projection of the condylar process on the midsagittal plane.
9. **Pharyngeal length (Naso-Oro):** The curvilinear distance along the posterior pharyngeal wall above the soft palate extending from the posterior nares to the level of the level of the true vocal folds (end of upper airway).
10. **Laryngeal descent:** The vertical distance from the PNS (posterior nasal spine) to the level of the thyroid notch (immediately superior to the thryroarytenoid muscles-true vocal folds).
11. **Hyoid bone descent:** The vertical distance from the PNS to the antero-inferior margin of the hyoid bone.

Statistical Analysis:
At each age i (i =1,2,3, ..., 220 months), we calculated the correlation coefficients (r) of each variable with VTL using a window of 28 months on either end of each age, then secured smoothed estimates using the same method. In other words, this calculation was repeated multiple times while moving/sweeping the window in one month increments across the entire developmental age range (birth-to-eighteen) yielding a continuous curve of r values. Next, the r-squared values were calculated and smoothed using splines to assess variability in VTL explained by the various VT structures i.e. assess relational growth of the different VT structures with VTL.

Figures 2 to 9 display the relational growth curves of the different VT structures with VTL for males and females. These figures represent the amount of variability in VTL which can be explained by the variation in each of the different VT structures. The r-squared value of .3 (.55 correlation), marked by a green reference line in the figures, was taken to be the p=.01 level of significance. Thus, relational growth curves above this level reflect the significance in the growth of particular structures in VTL variability.

Comparison of the relational growth curves of several VT structures with VTL is informative of similarities and/or differences in growth and contributions towards VTL.

RESULTS
Analysis results (smoothed r2 curves) are displayed graphically in Figures 2 to 9 demonstrating the relational growth of the different structures with VTL. As specified earlier, the green reference line at r^2 value of .3 reflects the .01 level of significance. Figures 8 & 9 display the relational growth of several different VT structures to compare and determine similarities/differences in relational growth with VTL.

Measured Variables — **Figures 2-9.** Smoothed r^2 curve fits for males (blue) and females (red) as a function of age. — **Figure Legends**

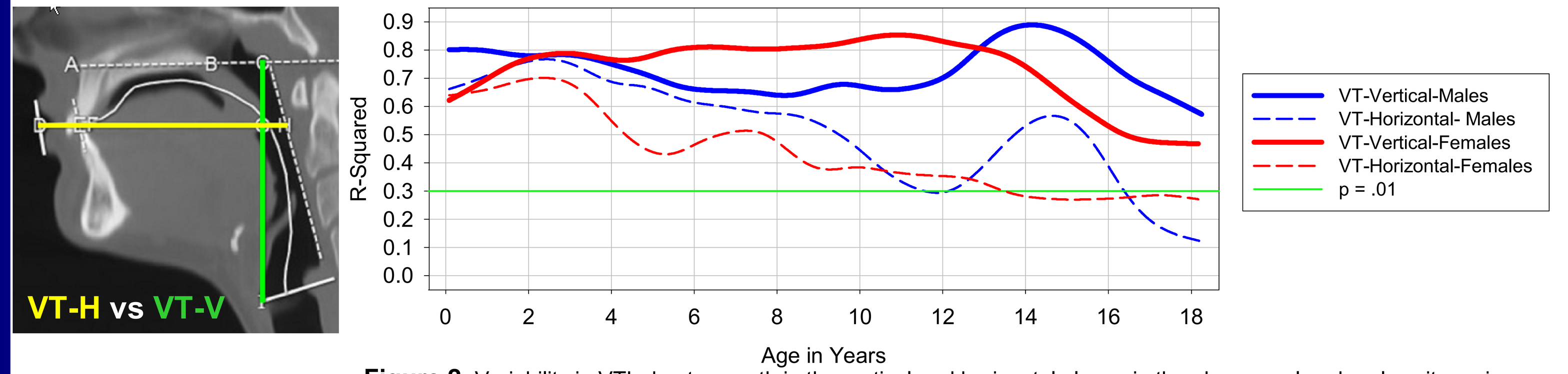


Figure 2. Variability in VTL due to growth in the vertical and horizontal planes in the pharyngeal and oral cavity regions

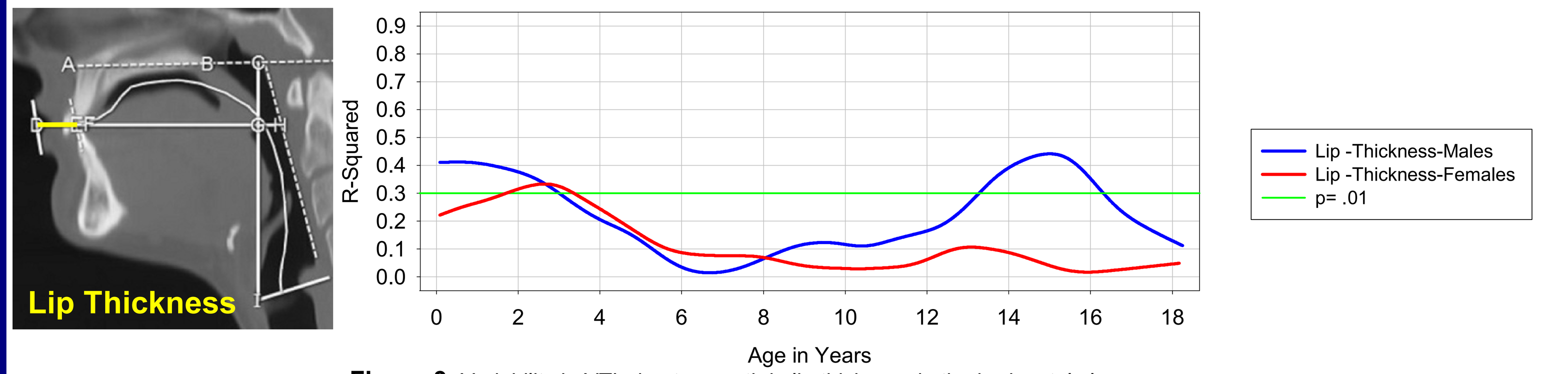


Figure 3. Variability in VTL due to growth in lip thickness in the horizontal plane.

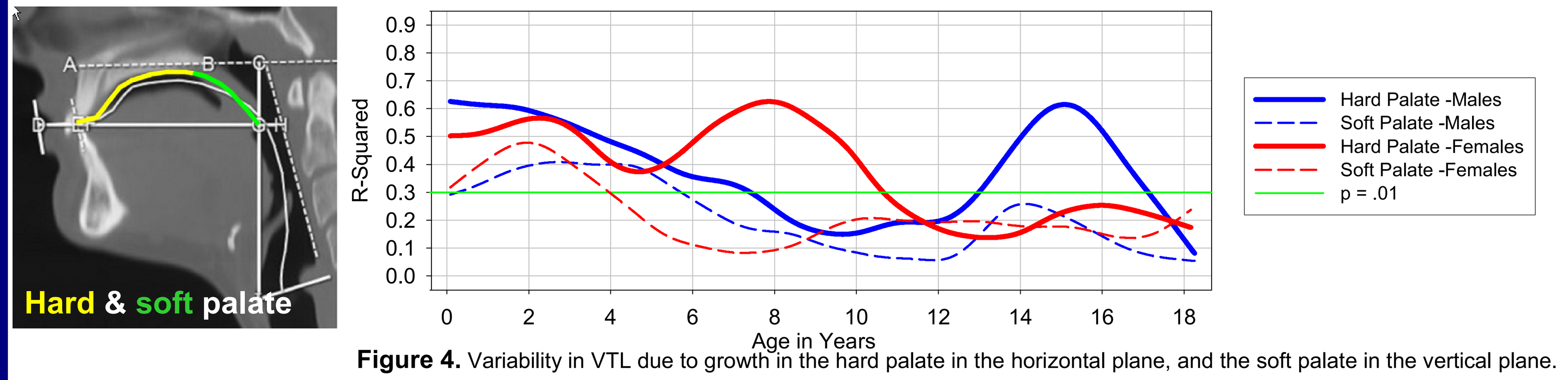


Figure 4. Variability in VTL due to growth in the hard palate in the horizontal plane, and the soft palate in the vertical plane.

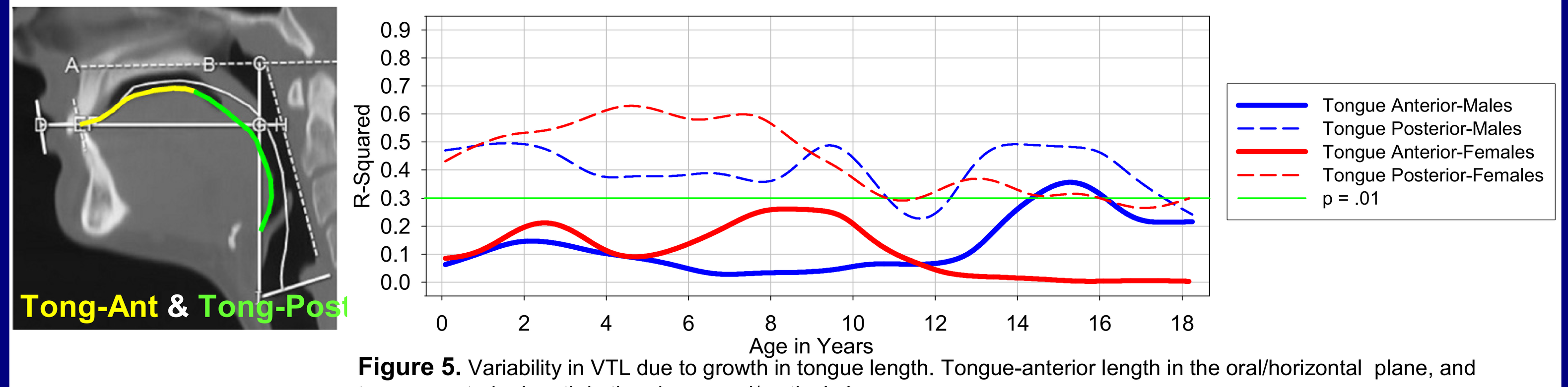


Figure 5. Variability in VTL due to growth in tongue length. Tongue-anterior length in the oral/horizontal plane, and tongue-posterior length in the pharyngeal/vertical plane.

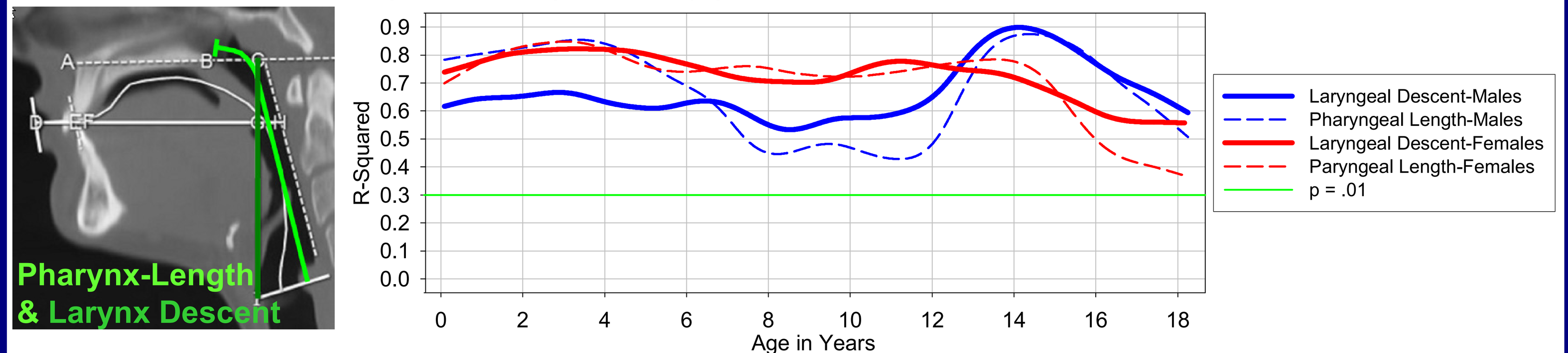


Figure 6. Variability in VTL due to growth in pharyngeal length and laryngeal descent in the vertical plane.

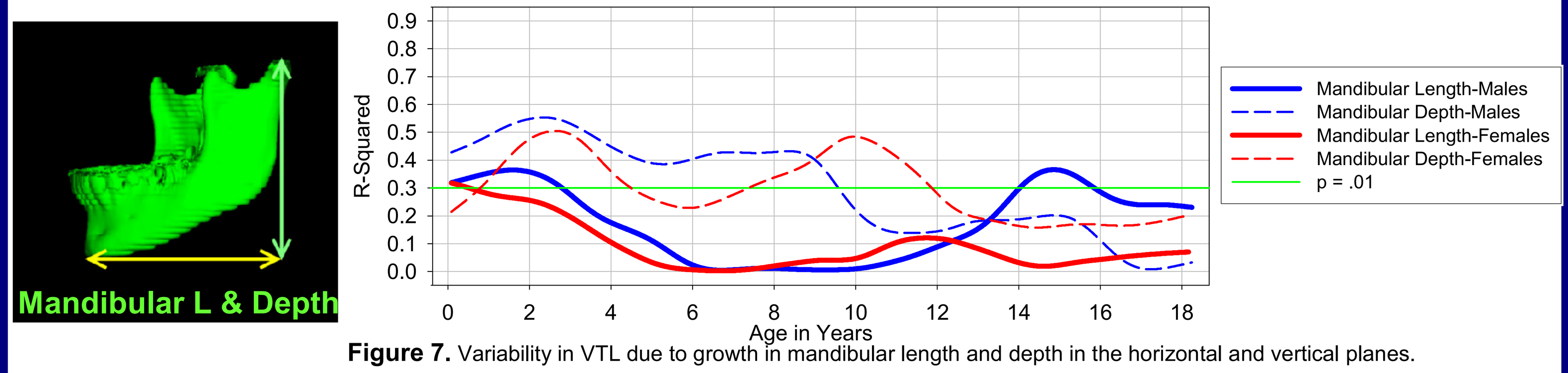


Figure 7. Variability in VTL due to growth in mandibular length and depth in the horizontal and vertical planes.

Figure 2-7 interpretations
- Findings show, for both males and females, significant growth in the vertical plane as well as in the horizontal plane throughout the first 18 years of life despite a slowing down of growth in the horizontal plane after age four. These findings are contrary to reports that growth of VTL is predominantly in the pharyngeal region or vertical plane.
- Also, findings show the presence of sex differences in plane of growth with differences emerging in females at about age four, and for males at about age nine. These novel anatomic findings are in line with some developmental acoustic observations [11, 16].

- The growth of lip thickness does not appear to affect VTL much, particularly in females.
- Lip thickness increases VTL variability in males during the adolescent years.

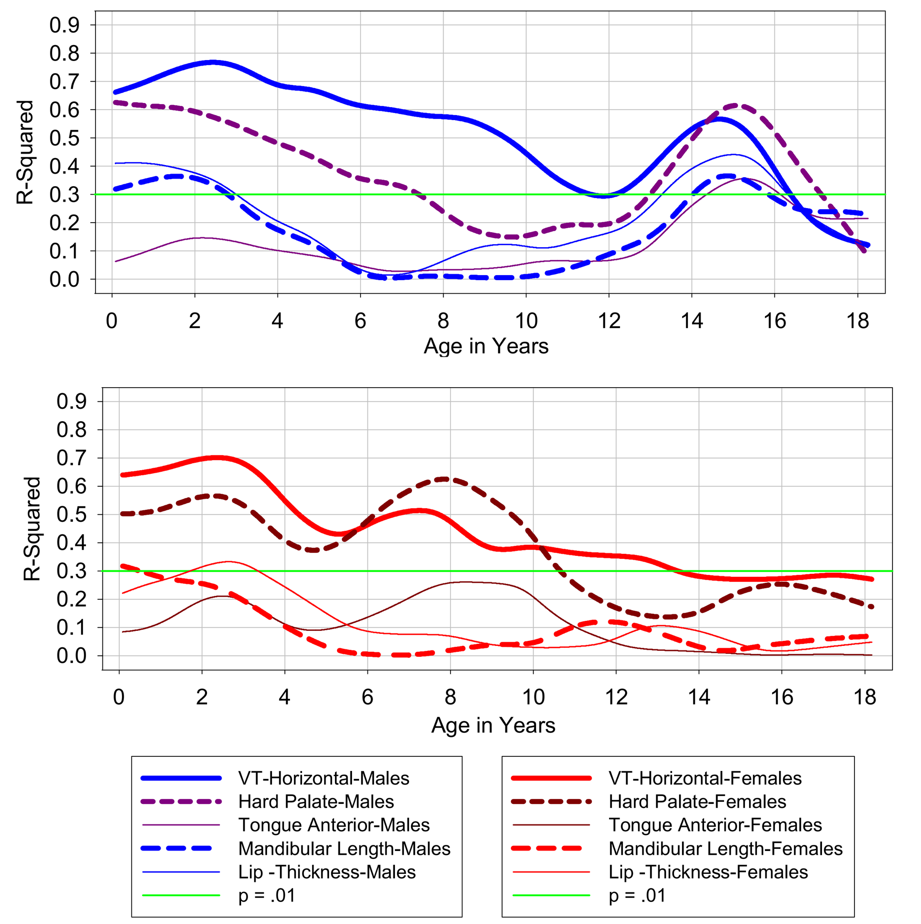
- The extent of relational growth of the palate with VTL changes during the course of development.
- The growth of both the hard and soft palates affects VTL for both males and females particularly during the first five years of life. However, after about age five, there are sex specific differences in the relational growth of the palates with VTL, particularly the hard palate. The increase in VTL is affected more by hard palate growth in females up to about age 10. In males, however, hard palate affects VTL between the ages birth to 6, and then again between the age 13 and 17 years.

- The relational growth of the posterior portion of the tongue with VTL is higher than tongue anterior throughout the course of development.

- The growth of pharyngeal length and laryngeal descent affect VTL throughout the course of development in both males and females. Note the extent of relational growth of laryngeal descent with VTL particularly in males.

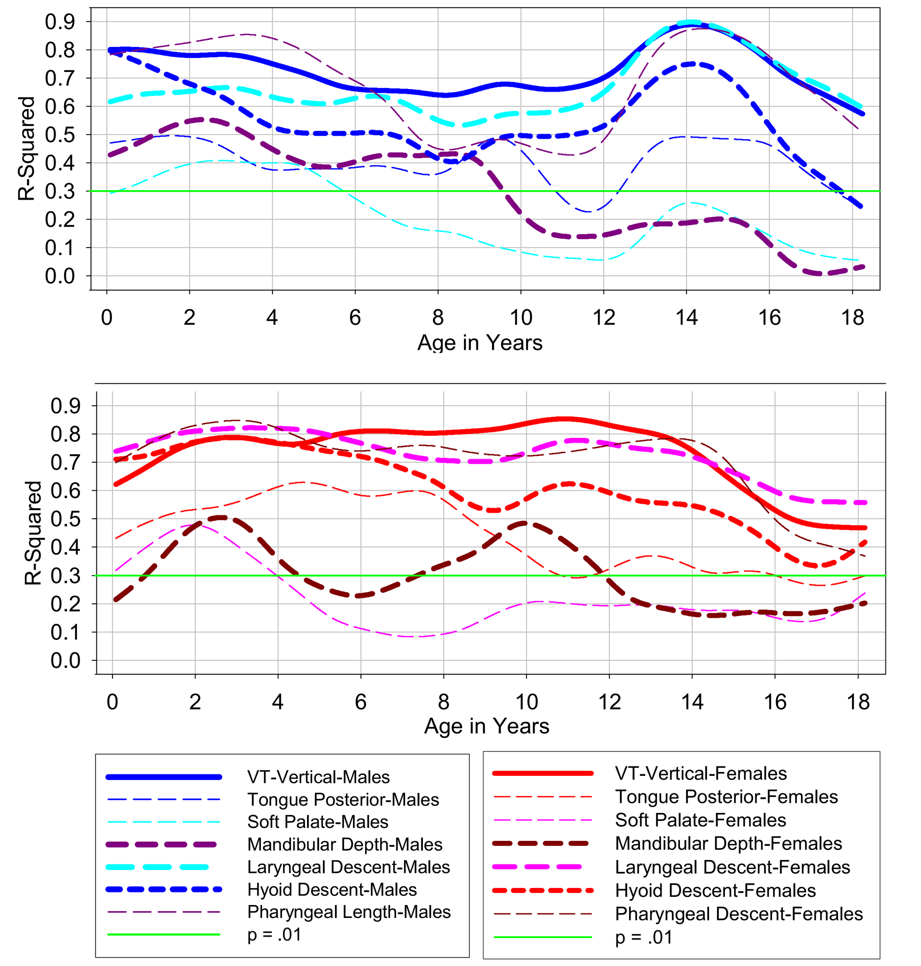
- The relational growth of mandibular depth in the vertical plane is higher than mandibular length for both males and females during approximately the first decade of life.

Figure 8. Variability in VTL due to growth of structures in the horizontal plane in males (top/blue) and females (bottom/red).



- Comparison of relational growth of hard and soft tissue structures with VTL in the horizontal plane between males (top) and females (bottom) in Figure 8 indicates less similarity in the relational growth of the different structures in females, particularly between the ages five to fourteen.

Figure 9. Variability in VTL due to growth of structures in the vertical plane. in males (top/blue) and females (bottom/red).



Comparison of relational growth of hard and soft tissue structures with VTL in the vertical plane in males (top) and females (bottom) in Figure 9 indicates less similarity in the relational growth of the different structures in both males and females up to about age 12-13.

DISCUSSION / MAJOR FINDINGS
- Findings indicate that most VT structures examined contribute towards it lengthening i.e. relational growth is present for all structures examined for both males and females. Also, findings support the notion of protracted growth throughout development [12]. The relative contribution of the different structures towards VTL, however, varies during the course of development [18].
- The developmental differences in the relative contribution of the different VT structures towards VTL are sex specific. Also, sex differences are present throughout development.
- The findings, particularly sex specific differences in the relational growth of VT-V and VT-H, can provide some explanation on the anatomic origin of reported prepubertal vowel formant frequency differences that are present by age four [11]; and the lower F3 (which affiliates with the oral cavity 5) in males with greater developmental dispersion [16].
- The comparison of the relational growth curves of several different VT structures (e.g. Figures 8 & 9) is informative of similarities (coordinated growth) and differences (asynchronous growth) in growth trends of the different VT structures with VTL. Such findings can help address questions of whether structures that function together to produce speech exhibit concurrent or coordinated growth throughout development [7, 13].
- The findings also strongly suggest that when studying variability, it is necessary to take into account detailed sex-specific information on developmental anatomy, in addition to the multitude of other critical variables – including the articulatory, aerodynamic, and respiratory systems, and their development as well as neural control – to ultimately reach a solid theoretical construct on motor speech development. As Thelen [15] emphasized, it is important to take information on developmental anatomy into account in theoretical constructs on speech development in children.

MAJOR CONCLUSION
- Information on developmental anatomy needs to be incorporated in the understanding of speech development, particularly motor control development.

ACKNOWLEDGMENTS
This work was supported by NIH/NIDCD grants # R03-DC 4362 & R01-DC 006282. Also, a core grant to the Waisman Center from NIH-NICHD P30-HD03352. Special thanks to Celia S. Choih for assistance with measurements, Katelyn J. Kassulke for assistance with data entry and figures, Abigail M. Mohoney, Carlyn A. Burris and Eric E. Schafer with poster preparation.

SELECT REFERENCES http://www.waisman.wisc.edu/vocal/

1. Arens, R., McDonough, J., Corbin, A., Hernandez, M., Maislin, G., Schwab, R., & Pack, A. (2002). Linear dimensions of the upper airway structure during development: Assessment by magnetic resonance imaging. American Journal of Respiratory and Critical Care Medicine, 165(1), 117-122.
2. Bosma, J. F. (1975). Anatomic and physiologic development of the speech apparatus. D. B. Tower (Ed.), The nervous system: Human communication and its disroders (Vol. 3, pp. 469-481). New York: Raven Press.
3. Chung, D., Chung, M., Durtschi, R.B., Gentry, L.R., & Vorperian, H.K.(2008). Measurement Consistency from Magnetic Resonance Images. Academic Radiology. 2008; 15(10), 1322-30.
4. Fant, G. (1960). Acoustic theory of speech production. The Hague: Mouton.
5. Fant G.(1975). A note on vocal tract size factors and non-uniform vowel normalization F-pattern scalings. Speech Transmission Laboratory Quarterly Progress and Status Reports: 22-30.
6. Fitch, W. T., & Giedd, J. (1999). Morphology and development of the human vocal tract: A study using magnetic resonance imaging. Journal of the Acoustical Society of America, 106(3), 1511-1522.
7. Fowler, C. A. (1980). Coarticulation and theories of extrinsic timing. Journal of Phonetics, 8, 113-133.
8. Gollin, E. (1981). Development and plasticity. E. Gollin (ed.), Development Plasticity (231-252). New York, NY: Academic Press.
9. Kent, R. D. (1981). Articulatory-acoustic perspectives on speech development. R. Stark (Ed.), Language behavior in infancy and early childhood (pp. 105-239). North Holland: Elsevier.
10. Kent, R. D. (1992). The biology of phonological development. C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), Phonological development: Models, research, implications (pp. 65-90). Timonium, MD: York Press.
11. Perry, T.L., Ohde, R.N., Ashmead, D.H. (2001).The Acoustic Bases for Gender Identification from Children's Voices. The Journal of the Acoustical Society of America, 109:2988-2998.
12. Sadagopan, N., Smith, A. (2008).Developmental changes in the effects of utterance length and complexity on speech movement variability. Journal of Speech, Language, and Hearing Research, 51(5), 1138-1151.
13. Saltzman, E. L., & Munhall, K. G. (1989). A dynamical approach to gestural patterning in speech production. Ecological Psychology, 1(4), 333-382.
14. Smith, B.L. (1994). Effects of experimental manipulations and intrinsic contrasts on relationships between duration and temporal variablility in children’s and adult’s speech. Journal of Phonetics, 22, 155-175.
15. Thelen, E. (1991). Motor aspects of emergent speech: a dynamic approach. N. A. Krasnegor, D. M. Rumbaugh, R. L. Schiefelbusch, & M. Studdert-Kennedy (Eds.), Biological and behavioral determinants of language development (pp. 339-362). Hilldale, NJ: Erlbaum.
16. Vorperian, HK, & Kent, R. (2007). Vowel Acoustic Space Development in Children: A Synthesis of Acoustic and Anatomic Data. Journal of Speech, Language, and Hearing Research, 50(6), 1510-1545.
17. Vorperian, H.K., Kent, R.D., Gentry, L.R. & Yandell, B.S. (1999). MRI procedures to study the concurrent anatomic development of the vocal tract structures: Preliminary results. International Journal of Pediatric Otorhinolaryngology, 49(3) 197-206.
18. Vorperian, H. K., Kent, R. D., Lindstrom, M. J., Kalina, C. M., Gentry, L. R., & Yandell, B. S. (2005). Development of vocal tract length during childhood: A Magnetic Resonance Imaging Study. Journal of the Acoustical Society of America, 117, 338-350.
19. Vorperian HK, Schimek ME, Wang S, Chung M, Kent R, Durtschi R, Ziegert AJ, Gentry LR. (2007). Anatomic Development of the Vocal Tract during the First Two Decades of Life: Evidence on Prepubertal Sexual Dimorphism from MRI and CT Studies. Poster Presented at the meeting of the Acoustical Society of America, New Orleans, LA. *http://www.waisman.wisc.edu/vocal/ASA%202007-5-Dec-2007-corrected-FINAL.pdf*