Development of vocal tract length during early childhood: A magnetic resonance imaging study[a)]

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Speech development in children is predicated partly on the growth and anatomic restructuring of the vocal tract. This study examines the growth pattern of the various hard and soft tissue vocal tract structures as visualized by magnetic resonance imaging (MRI), and assesses their relational growth with vocal tract length (VTL). Measurements on lip thickness, hard- and soft-palate length, tongue length, naso-oro-pharyngeal length, mandibular length and depth, and distance of the hyoid bone and larynx from the posterior nasal spine were used from 63 pediatric cases (ages birth to 6 years and 9 months) and 12 adults. Results indicate (a) ongoing growth of all oral and pharyngeal vocal tract structures with no sexual dimorphism, and a period of accelerated growth between birth and 18 months; (b) vocal tract structure's region (oral/anterior versus pharyngeal/posterior) and orientation (horizontal versus vertical) determine its growth pattern; and (c) the relational growth of the different structures with VTL changes with development—while the increase in VTL throughout development is predominantly due to growth of pharyngeal/posterior structures, VTL is also substantially affected by the growth of oral/anterior structures during the first 18 months of life. Findings provide normative data that can be used for modeling the development of the vocal tract.
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I. INTRODUCTION

As the infant vocal tract increases more than twofold in length from infancy to adulthood, its geometric proportions also change, so the term ''anatomic restructuring'' has been used to denote the physical changes that the vocal tract structures undergo during development. Reported changes include the bending of the vocal tract to form a right angle in the nasopharyngeal region; the disengagement of the velic–epiglottic contact; the descent of the larynx, the hyoid, and the epiglottis; as well as the descent of the posterior part of the tongue to form the anterior wall of the pharyx. See Fig. 1. (Bosma, 1975a, b, 1976, 1985; Crelin, 1976, 1973; Fried, Kelly, and Strome, 1982; Kent, 1981; Kent and Vorperian, 1995; Laitman and Crelin, 1976; Lieberman, 1977, 1984; Sasaki *et al.*, 1977; Westhorpe, 1987). The implication of such anatomic reorganization is that the various bony and soft-tissue structures in the oral and pharyngeal regions have different growth rates or growth patterns such that adult sizes are reached anywhere from age 7 to 18 years (Kent and Vorperian, 1995; Fitch and Giedd, 1999; Vorperian *et al.*, 1999; Lieberman *et al.*, 2001; Vorperian, 2000). Using advances in imaging technology, such as magnetic resonance imaging (MRI), the goal of our research is to quantitatively characterize the macroanatomic developmental changes in the bony and soft-tissue structures of the vocal tract during the first 2 decades of life. Our ultimate goal is to describe the

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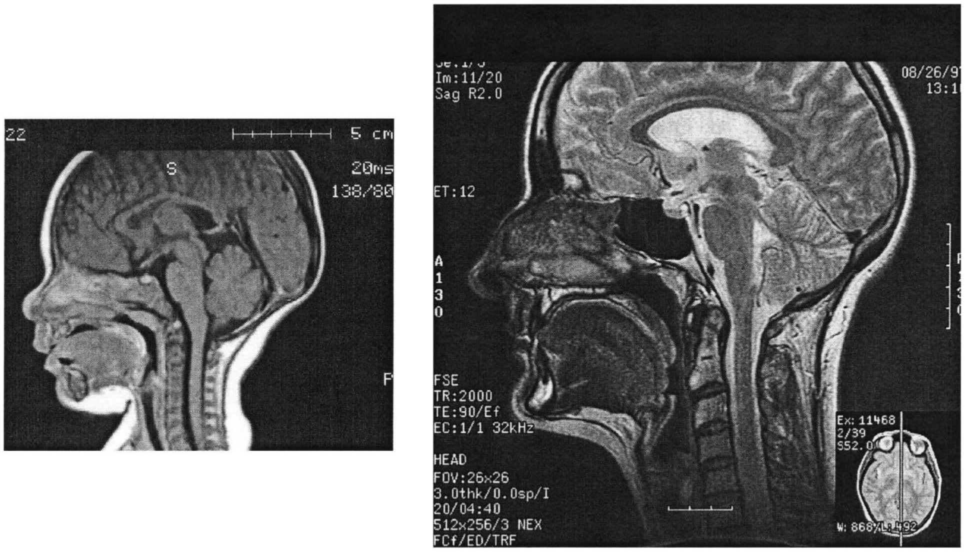

FIG. 1. Midsagittal magnetic resonance images of a 7-month-old female (left) and an adult female (right).

relational growth of those structures for the purpose of understanding the biological foundation of speech. Speech emergence and development is presumed to be dependent, at least in part, on the physical changes that the vocal tract structures undergo during development (Bosma, 1975a; Kent, 1976, 1981, 1992; Thelen, 1991). Also, the nature of the speech sounds that can be produced is determined in part by the physical constraints of the supralaryngeal system or the articulatory–resonatory system (e.g., Mowrer, 1980; Smith and Oller, 1981). This paper contains findings on the development of the various hard-and soft-tissue vocal tract structures and vocal tract length during the first 6 years of life as compared to the mature adult vocal tract. It also includes findings on developmental changes in the relational growth of those various vocal tract structures with vocal tract length. Relational growth is defined as the percent variation in vocal tract length explained by each of those various hard- and soft-tissue structures that affect vocal tract length.

Vocal tract length, defined as the curvilinear distance along the midline of the tract starting at the glottis to the intersection with a line drawn tangentially to the lips, has been estimated to increase from approximately 6 to 8 cm in infants to about 15 to 18 cm in adult females and males, respectively. Such estimates of vocal tract length have been calculated from acoustic studies (Fant, 1960) and from direct measurements of the adult vocal tract from radiographic images (Fant, 1960). More recently, Fitch and Giedd (1999), and Vorperian *et al.* (1999) reported vocal tract length measurements using MRI. Fitch and Giedd's data from subjects between the ages 2 and 25 years indicate significant length increases in all the different portions in the vocal tract. They report growth in the pharyngeal region to be prominent between early childhood and puberty, and even more pronounced between puberty and adulthood. Such findings support the hypothesis that an increase in vocal tract length is predominantly due to growth in the pharyngeal region (Kent and Vorperian, 1995; Vorperian, 2000). In this paper, rather than segmenting vocal tract length into different regions—such as oral and pharyngeal—the development of vocal tract length is examined in children as compared to the mature vocal tract in the adult by first independently examining all the oral and pharyngeal vocal tract structures in the sagittal plane, and then assessing the relational growth of each of those structures with vocal tract length. This latter assessment was done while taking into consideration the assigned region (oral versus pharyngeal versus combined) for each vocal tract structure. Structures examined, in the sagittal plane, include maxillary and mandibular lip thickness, hard and soft palate length, tongue length, mandibular length and depth, and the distance of the larynx, the epiglottis, and the hyoid bone from the posterior nasal spine (PNS). Such an approach was used to address the following objectives: (i) Determine the growth pattern that the various vocal tract structures follow. (ii) Determine the age or age range of accelerated growth periods, if such periods exist. (iii) Determine if there are gender differences in growth rate during the first 6 years of life. (iv) Examine differences in growth rate of the vocal tract structures based on region (anterior versus posterior) and orientation of plane of growth (horizontal versus vertical). Since the vocal tract is housed in the head and neck region, it is expected that the various vocal tract structures will follow the growth pattern and the plane of growth that the head and face follow (Farkas *et al.*, 1992a, b). (v) Assess the developmental changes in the relational growth of each vocal tract structure with vocal tract length.

II. METHODS

A. Subjects

MR images were secured from 37 white patients/subjects who received MRI for medical reasons known not to affect growth and development. The 37 subjects include 12 adult subjects (6 male, 6 female), and 25 pediatric subjects (16 male and 9 female). All adults and 9 pediatric subjects (6 male, 3 female) were imaged once, and the remaining 16 pediatric subjects (10 male, 6 female) were imaged two or more times. In this paper each MR imaging date is referred to as a case. The data reported are from 79 cases that include the 12 adult MRI cases, 9 pediatric MRI cases (6 male, 3 female) from the subjects imaged once, and 58 MRI cases

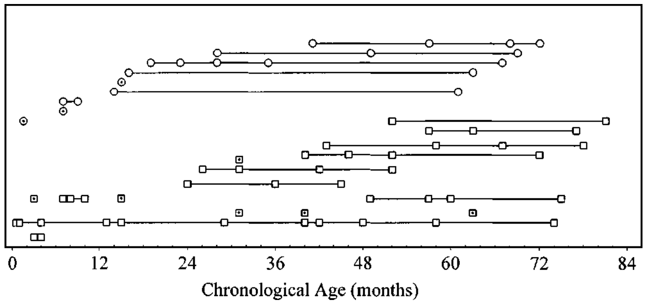

FIG. 2. Distribution of pediatric cases across chronological age in months. Square symbols denote male cases; round symbols, female cases. Repeat MRI cases are connected with a line. Nonrepeat cases have a dot in the symbol. Note that the frequency of repeat MRI cases does not exceed 2 weeks during the first month of life, and 1 month during the first year of life.

(40 male, 18 female) from the 16 pediatric subjects who received serial/repeat MRI. The age range of the pediatric cases is 2 weeks (0;.5) to 6 years 9 months (6;9). Figure 2 displays the distribution of the pediatric cases, and indicates that the frequency of repeat MRI cases does not exceed 2 weeks during the first month of life, and 1 month during the first year of life. The weights of the majority of the cases were at the 50th percentile reference growth curves for boys and girls, with all cases falling between the 25th to 95th percentile growth curves as per the National Center for Health Statistics growth charts (1976). No participants were significantly under- or overweight. The mean age of the 12 adult subjects was 23 years with mean height 166 and 171 cm; and mean weight 56 and 68 kg for females and males, respectively.

B. Procedures

Image acquisition methods have been described previously (Vorperian *et al.*, 1999). Basically, image acquisition involves two phases. The first phase is the actual MRI study, where virtually all of the pediatric patients were sedated using either chloral hydrate 50 mg/kg administered orally, or DPT (demerol, phenergan, and thorazine) 1 mg/kg administered intramuscularly, prior to entering the scanner. Once in the scanner, the facial structures of all subjects were placed centrally in the head coil using the laser lights of the MR imager (GE scanner or Resonex). All images were acquired during quiet respiration. MRI image acquisition parameters were as follows: The imaging matrix was 256×256 or 256 ×192 or 512×256. All images were obtained using a spin–echo pulse sequence or a fast spin–echo pulse sequence. Sagittal slices were obtained with T1-weighted sequences (repetition time [TR]=350 to 700 ms, echo delay time [TE]=14 to 30 ms) as well as T2-weighted sequences. The second phase of image acquisition involved digitizing the MR images by scanning all sagittal slices in the oral region into the computer using the UMAX Powerlook 2100XL oversized scanner with a transparency adapter, and storing the images for subsequent measurements. The DPI (dots per inch) setting was set to 600. When available, images with contrast injection, i.e., images acquired after intravenous administration of a contrast medium (Gadolinium-DTPA) to increase visualization of body tissues, were selected over images with no contrast injection.

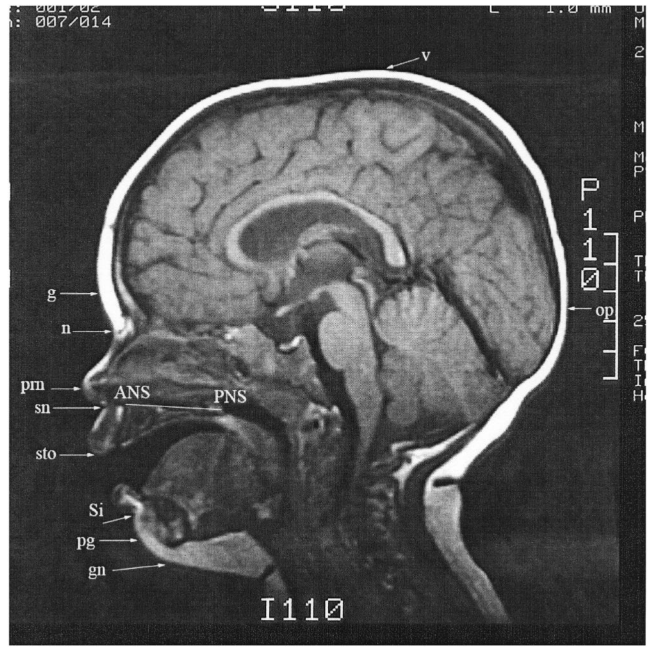

FIG. 3. Midsagittal magnetic resonance image of a 1-year, 3-month-old male subject with anatomic landmarks used for making measurements. ANS-PNS=anterior nasal spine–posterior nasal spine; g=glabella; gn =gnathion; n=nasion; op=opisthocranion; pg=pogonion; prn=pronasale; sto=stomion; sn=subnasale; Si=sulcus inferior or supramentale; v=vertex.

Data were acquired by measuring the following: *Maxillary and mandibular lip thickness*, *hard and soft palate length*, *naso-oro-pharyngeal length*, *laryngeal level*, *hyoid level*, *tongue length*, *mandibular length*, *mandibular depth*, and *vocal tract length*. Most measurements were made from the midsagittal plane, where distinct cerebral sulci extending to the corpus callosum are visible; also visible is the fourth ventricle, the full length of the cerebral aqueduct of Sylvius, the pituitary gland, part of the optic chiasm, the brainstem, and the cervical cord (Shorten *et al.*, 1994). In addition, the most distal parasagittal slices, where the condylar process of the mandible can be visualized, were used to calculate mandibular length and depth measurements. The image measurement software SIGMASCAN PRO by SPSS (formerly Jandel Scientific) was calibrated for each case/slice using the hash-scale mark on the MR image/slice. The measurement set for this study is described below. Refer to Fig. 3 for anatomic landmarks (Farkas, Posnick, and Hreczko, 1992a). Although most anatomic landmarks are evident in the midsagittal slice, sagittal slices immediately to the right and left of the midsagittal slice were used to ensure the accurate placement of anatomic landmarks to make measurements, particularly for structures that could deviate from midline such as the epiglottis and the uvula. The definition for each measurement follows: *Vocal tract Length*: The curvilinear distance along the midline of the tract starting at the thyroid notch to the intersection with a line drawn tangentially to the lips. The thyroid notch, which is slightly superior (about 5 mm in adults) to the anterior commissure—the junction of the vocal folds anteriorly in the larynx—was used as one of the two

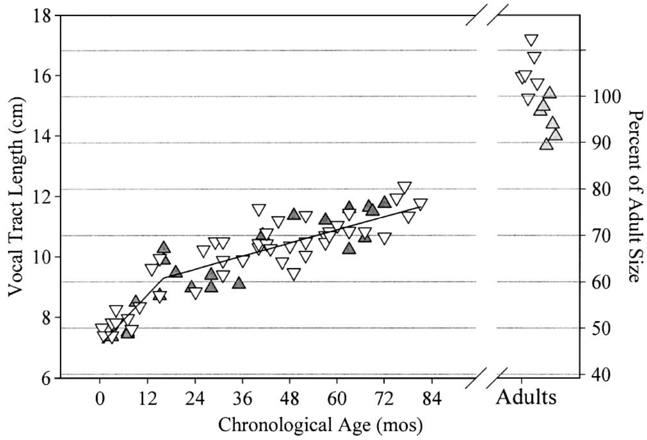

FIG. 4. Vocal tract length of the pediatric and the adult cases (open triangle down for males, and shaded triangle up for females). The second *Y* axis reflects the percent of adult size. Vocal tract length is defined as the curvilinear distance along the midline of the tract starting at the thyroid notch to the intersection with a line drawn tangentially to the lips.

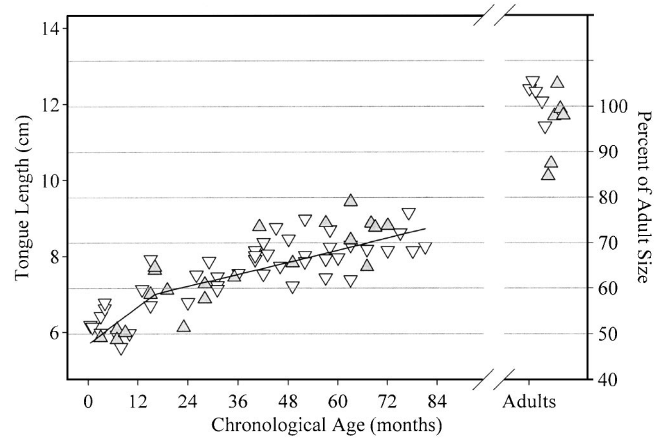

FIG. 5. Tongue length of the pediatric and the adult cases (open triangle down for males, and shaded triangle up for females). Tongue length is defined as the curvilinear distance along the dorsal superior contour of the tongue from the tongue tip to the valleculae.

end points of the vocal tract length measure instead of the conventional use of the glottis to ensure the visibility of this end point on midsagittal MRI. *Hard palate length*: 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, which is marked by the presence of increased fat and the beginning of curvature. *Soft palate length*: The curvilinear distance from the posterior edge of the hard palate to the inferior edge of the uvula. *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. *Tongue length*: The curvilinear distance along the dorsal superior contour of the tongue from the tongue tip to the valleculae. *Hyoid bone level or tongue level*: The vertical distance from the PNS (posterior nasal spine) to the level of the anterior inferior point of the hyoid bone. *Laryngeal level*: The vertical distance of a line drawn from the thyroid notch cartilage to the PNS (posterior nasal spine). *Naso-oro-pharyngeal length*: The curvilinear distance along the posterior pharyngeal wall above the soft palate extending from the posterior naris to the end of the upper airway. A line drawn horizontally from the superior border of the hyoid bone to the posterior pharyngeal wall was taken as the dividing line between the nasopharynx and the oropharynx. *Maxillary lip thickness*: The anteroposterior distance from the subnasale (sn) to the anterior nasal spine (ANS). *Mandibular lip thickness*: The horizontal anteroposterior distance from the sulcus inferior (Si) or supramentale to the hard tissue line.

C. Statistical analysis

Measurement error includes a small calibration error and an error due to measurement. The calibration error, which occurs during software calibration while assigning the number of pixels per 1-cm hash marks, is in the range of 0.1 to 0.4 mm. This error was unavoidable since the different MR images had different specification with respect to matrix size and FOV (field of view). To compute the standard deviation (σ) of error due to measurement, duplicate measurements were made on 22 different hard- and soft-tissue structures, from nine cases at three different ages (15, 40, and 63 months). Duplicate measurements were made at two independent times with an interval of 1 month. The standard deviation of measurement error was independent of age ($\sigma=0.14$ cm; $n=53$ at age 15 mos; $\sigma=0.18$ cm; $n=52$ at age 40 mos; $\sigma=0.16$ cm; $n=48$ at age 63 mos). Thus, the accuracy of visualizing the various soft and particularly bony structures on MRI does not change during the course of development since the measurement error is approximately the same at the different ages examined. For all subjects, the standard deviation of measurement error for hard-tissue structures ($\sigma=0.22$ cm; $n=79$) was larger than for soft-tissue structure ($\sigma=0.12$ cm; $n=74$). This was expected since it is difficult to determine the exact borders of bony structures in the oral-pharyngeal region on MRI (Katzberg and Westersson, 1991). Also, since the absolute size of the measurements varies (e.g., large values for vocal tract length and small values for lip width), the percent measurement difference (time 1 versus time 2) of the length of the struc-

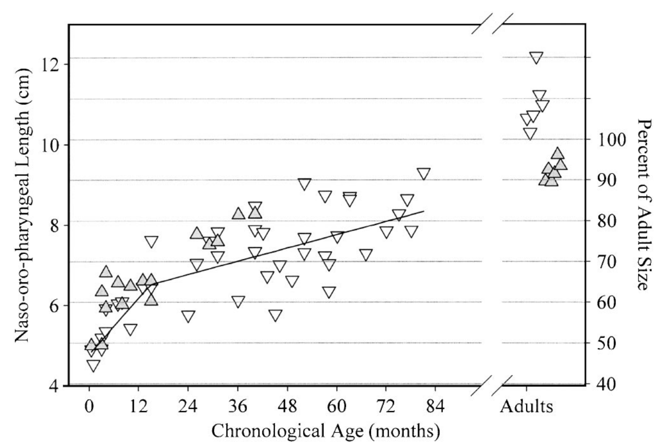

FIG. 6. Pharyngeal length of the pediatric and the adult cases (open triangle down for males, and shaded triangle up for females). Naso-oro-pharyngeal length is defined as the curvilinear distance along the posterior pharyngeal wall above the soft palate extending from the posterior naris to the level of the thyroid cartilage or the end of the upper airway.

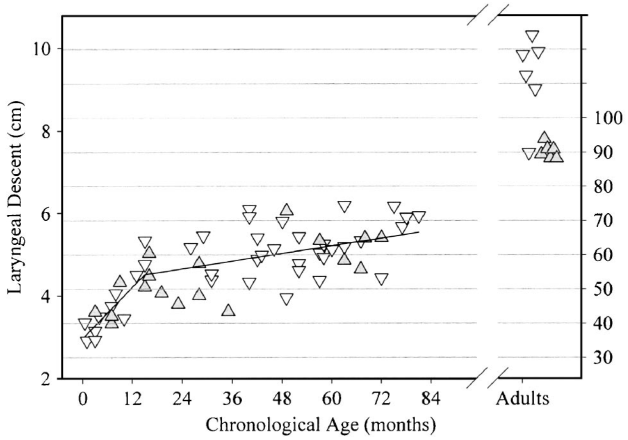

FIG. 7. Laryngeal descent of the pediatric and the adult cases (open triangle down for males, and shaded up triangle for females). Laryngeal descent is defined as the vertical distance of a line drawn from the thyroid notch to the PNS (posterior nasal spine).

tures remeasured, was examined individually for the nine cases. The maximum percent deviation between measurements was as follows: No more than 3% for vocal tract length, less than 5% for pharyngeal length and tongue length, less than 6.5% for total length for hard and soft palates, and less than 8% for mandibular length and depth.

1. Anatomic growth of the vocal tract structures

The absolute growth (male versus female measurements) of the different hard- and soft-tissue vocal tract structures during the first 6 years of life and in adults is graphically presented in Figs. 4 to 11. The broken line growth curve model was used to fit the data because it allows a test for a change in the rate of growth, and provides an estimate of the time of the change or the "breakpoint" (Bacon and Watts, 1971). The broken line consists of two straight lines joined at a point. It has the form $a+b$ (ca.mos) for ca.mos $\leqslant p$ and $d+c$ (ca.mos) for ca.mos $>p$, where $d=(a-b)/p+c$ is determined by the restriction that the two lines must meet at ca.mos$=p$ (ca.mos stands for chronological age in months). The intercept parameter (a) is assumed random in

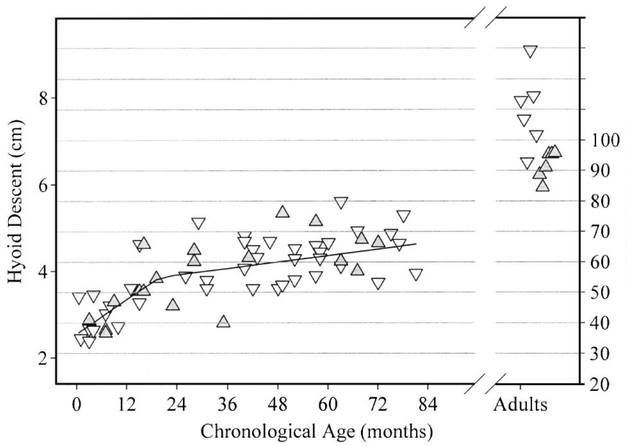

FIG. 8. Hyoid descent of the pediatric and the adult cases (open triangle down for males, and shaded triangle up for females). Hyoid bone level or tongue level is defined as the vertical distance from the PNS to the level of the antero-inferior point of the hyoid bone.

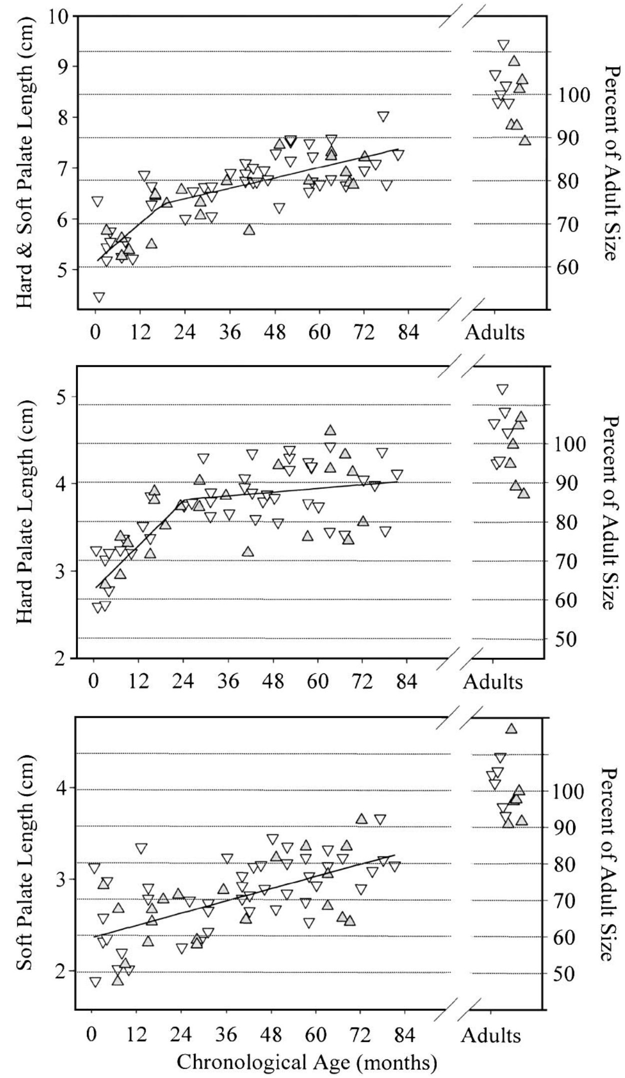

FIG. 9. Hard and soft palate length (top figure), hard palate length (middle figure), and soft palate length (bottom figure) development for pediatric and adult cases (open triangle down for males, and shaded triangle up for adult females. Hard palate length is defined as the curvilinear distance along the hard palate contour from the anterior point of the incisor or tooth bud to the beginning of the soft palate, which is marked by the presence of increased fat and the beginning of curvature. Soft palate length is defined as the curvilinear distance from the posterior edge of the hard palate to the inferior edge of the uvula.

the population of subjects and accounts for within-subject correlation. The S-plus NLME software was used for estimating the parameters in this nonlinear mixed effects model. These data were fit with a broken line growth curve model both with and without the inclusion of terms for gender effects. The Wald F-test was used to test for the effect of gender (Pinheiro and Bates, 2000).

2. Growth of vocal tract structures based on region/ orientation

Using the angular bend of the vocal tract, the measurements of the various hard- and soft-tissue vocal tract structures were assigned to one of the following three regions/ orientations: (i) Anterior or oral structures that grow in the horizontal plane [i.e., run parallel to head length—the distance from the glabella (g) to the opisthocarnion (op)]. Mea-

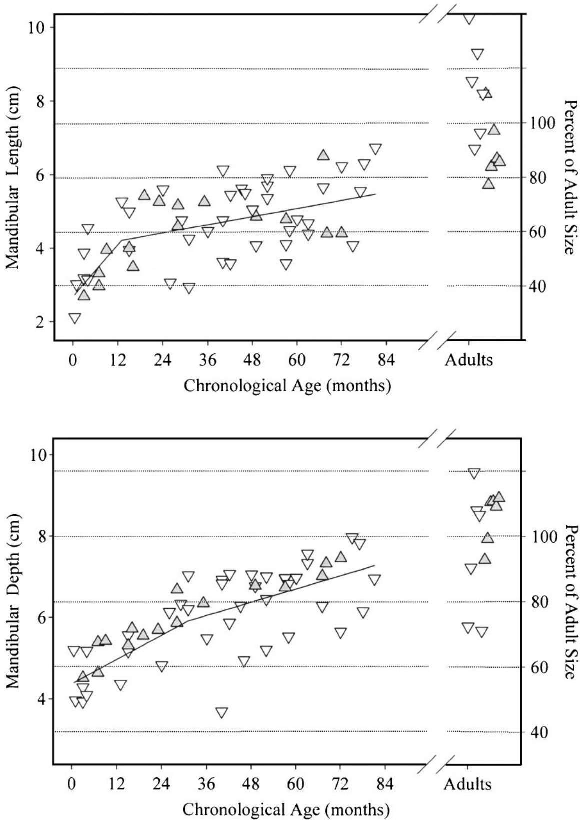

FIG. 10. Mandibular length (top figure) and mandibular depth (bottom figure) development for pediatric cases and adult cases (open triangle down for males, and shaded triangle up for females). Mandibular length and depth are defined as the horizontal and vertical distances in the midsagittal plane from the mental protuberance to the orthogonal projection of the condylar process on the midsagittal plane.

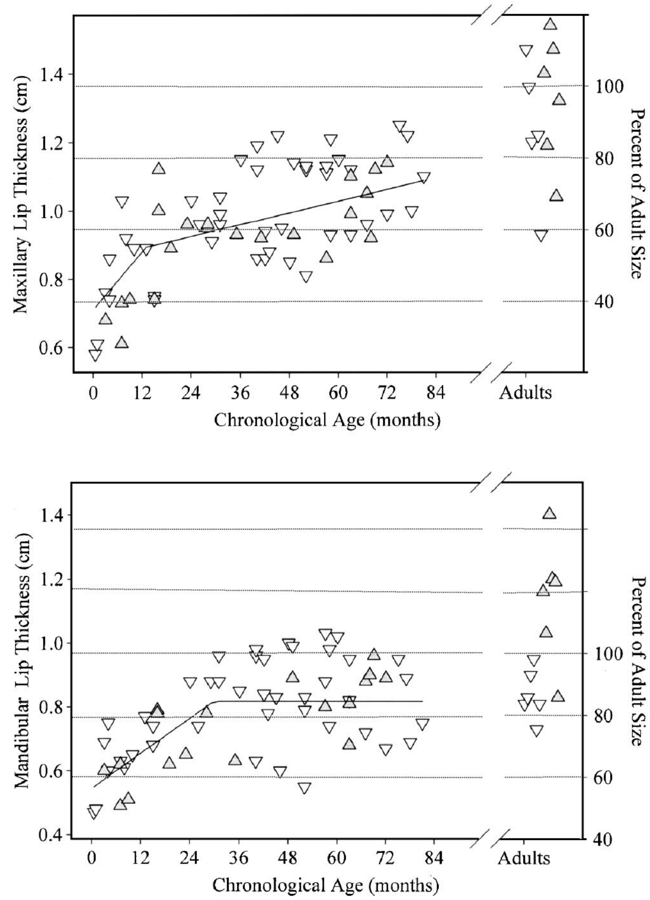

FIG. 11. Maxillary lip thickness (top figure) and mandibular lip thickness (bottom figure) for pediatric cases and adult cases (open triangle down for males, and shaded triangle up for females. Maxillary lip thickness is defined as the antero-posterior distance from the subnasale (sn) to the anterior nasal spine (ANS). Mandibular lip thickness is defined as the horizontal antero-posterior distance from the supramentale to the hard-tissue line.

surements included were the maxillary and mandibular lip thickness, hard palate length, and mandibular length. (ii) Posterior or pharyngeal structures that grow mostly in the vertical plane (i.e., run parallel to facial height [the distance from the nasion (n) to gnathion (gn)]. Measurements included were soft palate length, pharyngeal length, hyoid, and laryngeal descent. (iii) Combined (anterior and posterior) structures, that grow in both the horizontal and vertical planes. Measurements included were vocal tract length and tongue length. Using the estimated breakpoints that varied over the structures in the above-described broken line model (see Table I), the effect of pre- versus postbreakpoint segment (i.e., initial versus final slope) and structure region/orientation (i.e., anterior/horizontal versus posterior/vertical versus combined) on slope was investigated using a nested analysis of variance with adult structure size included as a covariate. This was followed by pairwise comparisons of the three regions/orientations using the least significant difference method.

3. Relational growth of the different vocal tract structures with vocal tract length

The estimated breakpoints varied over the structures in the above described broken line model (Sec. II C 1). A typical breakpoint value of 18 months was chosen in order to divide pediatric subjects into two groups. These groups were then used to assess the developmental changes in the relational growth of the different vocal tract structures with vocal tract length. This was achieved by calculating the between-subject *r*-squared statistic (between-subject correlation coefficient of each structure with vocal tract length squared) and then comparing these values across the different structures and the different age groups. The *r*-squared statistic is the percent of subject-to-subject variation in vocal tract length explained by other structures (a growth measurement).

III. RESULTS

A. Anatomic growth of the vocal tract structures

All available measurements from the 69 pediatric cases, between the ages 2 weeks to 6 years 9 months, and the 12 adults are plotted in Figs. 4 to 11, with growth curve fits for the pediatric data and a second Y axis referencing the pediatric data to the percent of the average adult size. The figures depict the development of *vocal tract length* (Fig. 4), *tongue length* (Fig. 5), *naso-oro-pharyngeal length* (Fig. 6), *laryngeal descent* (Fig. 7), *hyoid decent* (Fig. 8), *hard and soft palate length* (Fig. 9), *mandibular length*, and *mandibular depth* (Fig. 10), and *maxillary and mandibular lip thickness*

TABLE I. Parameter values with standard error (SE) of the broken line growth curve model described. (a) intercept; (b) slope term for ages less than the breakpoint (brk); (c) slope term for ages greater than the breakpoint; and (brk) the estimated breakpoint in chronological age (ca) in months.

	a	SE (*a*)	*b*	SE (*b*)	*c*	SE (*c*)	brk	SE (brk)
Vocal tract length	7.079	0.028	0.139	0.021	0.036	0.131	15.935	2.803
Tongue length	5.681	0.033	0.082	0.019	0.027	0.166	16.007	4.857
Pharyngeal length	4.772	0.054	0.117	0.037	0.027	0.196	14.964	5.178
Laryngeal descent	2.966	0.067	0.103	0.030	0.015	0.317	14.990	4.476
Hyoid descent	2.545	0.068	0.066	0.018	0.012	0.476	19.884	5.801
Palate (hard and soft)	5.155	0.034	0.064	0.018	0.017	0.258	17.830	5.645
Hard palate	2.787	0.039	0.043	0.008	0.004	0.804	24.212	3.739
Soft palate	2.362	0.036	0.011	0.002	NA	NA	NA	NA
Mandibular length	2.657	0.133	0.120	0.078	0.018	0.382	12.936	8.446
Mandibular depth	4.374	0.057	0.049	0.013	0.027	0.329	30.976	14.562
Maxillary lip thick	0.711	0.064	0.014	0.007	0.003	0.313	13.017	7.151
Mandibular lip thick	0.545	0.070	0.009	0.002	NA	NA	29.767	5.512

(Fig. 11). Figure 4 shows that the development of vocal tract length increases from birth to age 6 years 9 months, with a somewhat more rapid growth during approximately the first 16 months of life. The vocal tract length measurements for children between 2 to 6 years as well as the adults are in congruence with data reported by Fitch and Giedd (1999) using MRI procedures. The average vocal tract length by age 18 months is 8.3 cm, which, as plotted on the second *Y* axis of Fig. 4 labeled ‘‘percent of adult size’’, is a measure that is about 55% the adult vocal tract length; and at age 6 years, the average length is 11.4 cm, which is about 75% the adult vocal tract length. Figures 5 to 11 depict the development of the various hard- and soft-tissue structures that contribute towards vocal tract lengthening. Most structures, despite differences in growth rate, appear to follow a growth pattern or a growth curve that is similar to that of the vocal tract length. That is, most structures appear to have an ongoing growth from age 2 weeks to age 6 years 9 months with a somewhat more rapid growth during approximately the first 18 months of life. At about age 18 months, the various vocal tract structures achieve between 55% to 80% of the adult size, and at about age 6 years, they are between 65% to 85% of the adult size. Such percentage ranges indicate that some structures get closer to their adult mature size sooner than others. For example, the hard palate length and maxillary lip thickness (both anterior or oral structures) are at 80% of their adult mature size by age 18 months; however, other structures, such as mandibular depth and pharyngeal length (predominantly posterior or pharyngeal structures), reach 80% of their adult mature size by about age 6 years. Other structures such as laryngeal descent (65%), hyoid descent (65%), and tongue length (70%), continue to undergo considerable growth after age 6 until they reach their adult mature size.

The observation of a more rapid rate of growth during early childhood (depicted in Figs. 4 to 11) was statistically supported by modeling the relationships between age and each of the vocal tract structures of the pediatric data with the broken line growth curve model. As noted above (Sec. II C 1), this model was used because it allows testing for a change in the rate of growth, and provides an estimate of the time of the change or the ‘‘breakpoint.’’ Table I lists the estimated parameters and their standard errors. The mean value for the intercept term ‘‘*a*’’ is used in the fitted model curves plotted in Figs. 4 to 11. As seen in Table I, with the exception of the soft palate that does not have a breakpoint (brk) (i.e., one line fits all the data), the growth rate for most structures is faster prebreakpoint than postbreakpoint. That is, the slope terms *b* (prebreakpoint) are generally greater than slope terms *c* (postbreakpoint; $p<0.0001$). Also, growth continues postbreakpoint ($c>0$) for most structures except for mandibular lip thickness, which has a zero slope (horizontal) for the second segment (postbreakpoint). We also fit models with random slope terms (*b* and *c*) and random breakpoints, but likelihood ratio tests indicated that these models did not improve the fit significantly. All vocal tract measurements were transformed to the log scale to stabilize the variance. Furthermore, we tested for differences due to gender by comparing a general model which allows the (mean) parameter values to vary by gender to a simpler model which ignores gender. In all cases the effect of gender was not significant ($p>0.05$). The need for a more complex within-subject correlation structure was also explored by comparing a within-subject independence to autoregressive serial correlation. Once again, the fit of the more complex model was not a significant improvement.

B. Growth of vocal tract structures based on region/orientation

The different vocal tract structures were grouped into three region/orientation classes (i.e., anterior/horizontal versus posterior/vertical versus combined (see Sec. II C 2). The effect of these classes on the slopes was significant ($p=0.019$). The interaction term, however, was not significant ($p=0.654$), indicating that the pattern of differences in slopes between the three regions/orientations was consistent across segments (pre- and postbreakpoints). Pairwise comparisons of these three regions/orientation classes found significant differences among all pairs: vertical versus horizontal $p=0.013$; combined versus vertical $p=0.026$; combined versus horizontal $p=0.0006$. Table II lists the means for region/orientation of pre- and postbreakpoint segments. Note that the means are larger prebreakpoint than postbreakpoint, and that the ordering of the means (combined>vertical

TABLE II. Means of initial slope (prebreakpoint segment) and final slope (postbreakpoint segment) separated by region/orientation. SE indicates standard error. See the text for the vocal tract structures' region/orientation assignment.

Region/orientation	Mean initial slope prebreakpoint segment	SE	Mean final slope postbreakpoint segment	SE	*n*
Anterior/horizontal	0.046	0.022	0.006	0.004	12
Posterior/vertical	0.069	0.020	0.019	0.004	12
Combined	0.095	0.026	0.027	0.005	12

>horizontal, which reflects the order of growth) is the same for the initial slope (prebreakpoint segment) and final slope (postbreakpoint segment).

C. Relational growth of the different vocal tract structures with vocal tract length

As noted in Table I, the different structures have different breakpoints (brk) ranging from 13 months (e.g., mandibular length) to 31 months (e.g., mandibular depth). It is therefore difficult to compare growth rates (i.e., slopes) across structures. In order to assess the amount of variability in vocal tract length which can be explained by the variation in each of the other structures (i.e., to assess the relational growth of the different vocal tract structures with vocal tract length), we first divided the subjects into three groups (two pediatric groups and one adult group), and then computed the between-subjects *r*-squared statistic for all the structures in each group. The pediatric subjects were divided into two groups using the age of 18 month as the dividing value. This decision was based on the 95% confidence intervals for the estimated breakpoints, and age 18 month was chosen as a compromise between the median estimated breakpoint for the vocal tract measurements (16 months) and the transition point indicated by the acoustic data (24 months) (Robb *et al.*, 1997; Gilbert *et al.*, 1997). In all but one case (mandibular lip thickness) the 95% confidence intervals for the estimated breakpoints included 18 months. Thus, the first pediatric group (peds I; $n=19$) consisted of cases between the ages of 2 weeks and 18 months. The second pediatric group (peds II; $n=48$) consisted of cases ages 19 months to 6 years and 9 months. The third group (adults; $n=12$) consisted of adults with vocal tract structures that have reached their mature size. The adult group was included to assess the pediatric data in terms of percent of adult size as discussed above (right-hand second *Y* axis in Figs. 4 to 11), and to compare the relational growth of the different vocal tract structures with vocal tract length during the course of development. For each group, the between-subject *r*-squared was calculated (between-subject correlation coefficient of each structure with vocal tract length squared). The between-subject *r*-squared is the percent of variability in vocal tract length among subjects explained by that measurement. The *r*-squared calculations were not sensitive to small changes in the breakpoint, i.e., the results and conclusions outlined below were not altered when the data were analyzed using different cutoff ages, such as 16 or 24 months, for the pediatric data.

Figure 12 is a squares plot that represents the percent relational growth by the size (volume) of the squares. Larger squares indicate more relational growth. For all three groups (with the exception of the hard palate in the peds II group and of mandibular depth in adults) all hard- and soft-tissue vocal tract structures demonstrate concurrent or relational growth with vocal tract length. However, the extent of relational growth changes for each structure during the course of development. The first column of Fig. 12 lists in order the percent relational growth of the various structures with overall vocal tract length for the first pediatric group, peds I. The second and third columns reflect the percent relational growth for the second pediatric group, peds II, and adults. For all three age groups, naso-oro-pharyngeal length, tongue length, and laryngeal descent have the highest relational growth with vocal tract length. However, comparison of the percentages for each of those structures, as well as of the remaining structures, across the three groups indicates that the extent of relational growth changes (decreases or increases) during the course of development. For example, pharyngeal length is the largest for peds I (82%) and adults (66%), but the third in line for peds II (57%). In contrast, laryngeal descent is the largest for peds II (66%) but the third largest for peds I (67%) and adults (45%). Such differences in order and percent variation explained appear to stem from differences in growth in the naso-pharyngeal region (horizontal plane) versus the oro-pharyngeal region (vertical plane). This inference is based on examining change in structures in the naso-oro-pharyngeal region, namely, palatal length and laryngeal descent. The former structure is below the posterior naris where the naso-pharynx measure starts, and the latter structure is where the oro-pharynx measure ends. In peds I and in adults, the percent variation explained by the hard palate (58% and 22%) is more than the soft palate (2% and 16%). However, for peds II, the hard palate (0.01%) has barely any relational growth with vocal tract length. Thus, it appears that in peds I and in adults there are developmental changes, in the horizontal plane, at the beginning of where the measure of the naso-pharynx is initiated. Thus, during the course of development, there are not only differences in the extent of relational growth of the different vocal tract structures with vocal tract length (decreases or increases), but differences in relational growth based on structure region/orientation (anterior/horizontal versus posterior/vertical). Indeed, comparison of the various structures listed in Fig. 12 based on region (anterior versus posterior) and orientation or plane of growth (horizontal versus vertical) indicate that during approximately the first 18 months of life (peds I group) there is about as much growth and subsequently relational growth of the anterior structures in the horizontal plane—such as hard palate length (58%)

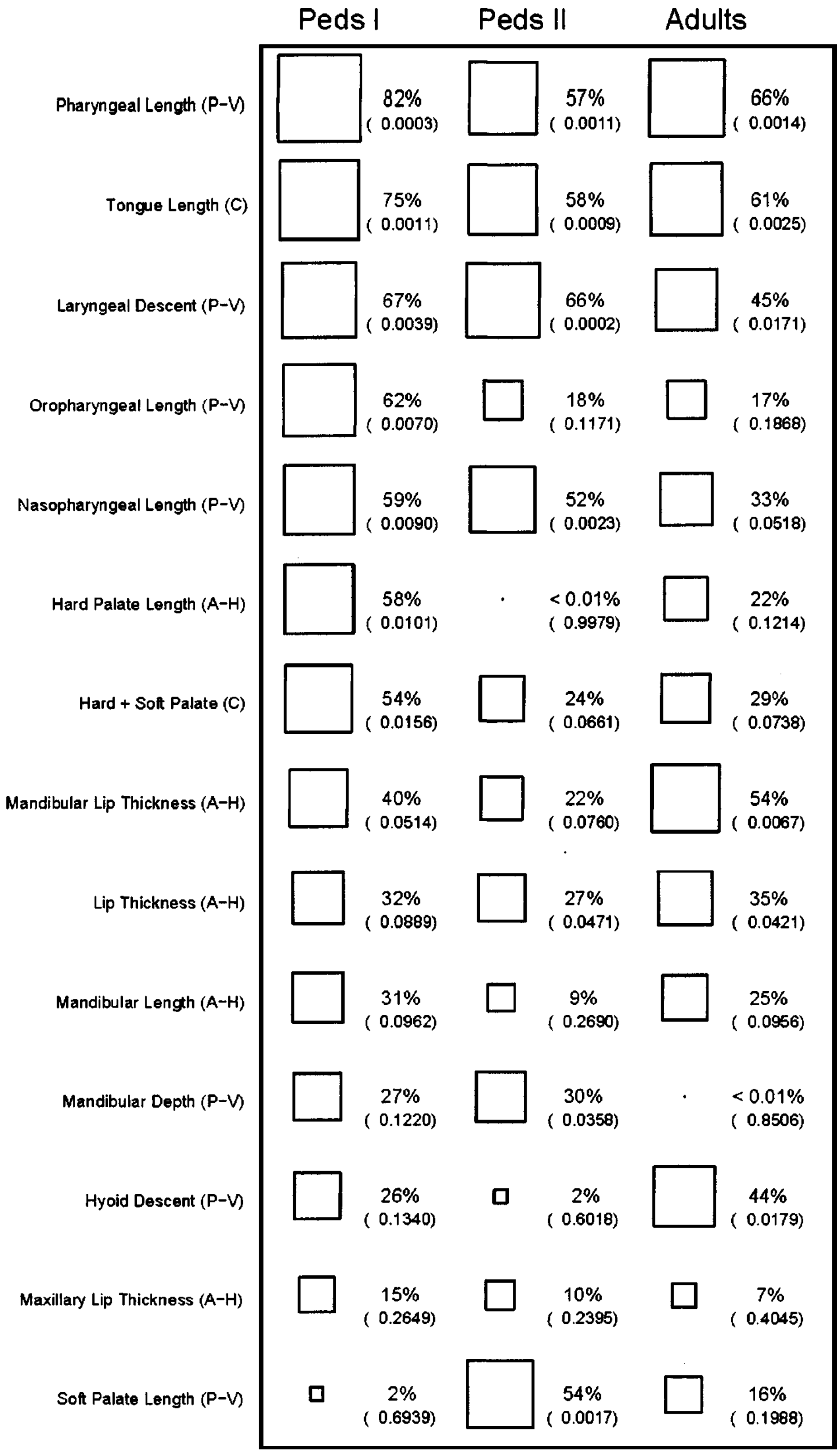

FIG. 12. Squares plot showing the *r*-squared or percent variability in vocal tract length explained by the various vocal tract structures. The area of the squares is proportional to *r*-squared. The numbers in parentheses represents the *p* value for the test where *r*-squared is different from zero. Structures include pharyngeal length (naso+oro pharyngeal lengths), tongue length, laryngeal descent, palate length (hard+soft palate lengths), lip thickness (average maxillary +mandibular lip thickness), mandibular length, mandibular depth, and hyoid descent. Each structure is followed by its region/orientation: P–V (posterior/vertical); A–H (anterior/horizontal); and C (combined anterior/horizontal and posterior/vertical). Note that the listed order of structures is based on the percentages for peds I only. The percent vocal tract variability explained changes (increases or decreases) for each group (peds I, peds II, and adults).

and mandibular length (31%)—as there is growth of the posterior structures in the vertical plane—such as laryngeal descent (67%), mandibular depth (27%), and hyoid descent (26%). In contrast, from the ages of 19 months to 6 years and 9 months (peds II group), the growth, and subsequently the relational growth, of most of the posterior structures in the vertical dimension, such as laryngeal descent (66%), soft palate length (54%), and mandibular depth (30%), exceeds the growth of the anterior structures in the horizontal plane, such as mandibular length (9%) and hard palate length (0.01%). Similarly, for the adults' group, the growth and consequently the relational growth of the posterior structures with vocal tract length, such as laryngeal descent (45%), and hyoid descent (44%), exceeds that of the anterior structures, such as mandibular length (25%), hard palate length (22%), and lip thickness (35%). Thus, although there is notable growth for most structures in both the vertical and horizontal planes at all age groups, growth in the horizontal plane slows down for peds II, but then increases at some later point to reach the mature adult size.

IV. DISCUSSION

A. Current findings

The current data from sagittal MRI slices provide detailed developmental information on the changes that the various hard- and soft-tissue structures undergo, and their relational growth with vocal tract length. These data are without precedent in that they were obtained from children from birth to age 6 as well as adults, and thus they capture an age range—specifically birth to age 4—where most of the important anatomic restructuring occurs. Current findings, as discussed below, indicate that (a) there is ongoing growth, with no sexual dimorphism, between birth and age 6 years 9 months and a period of accelerated growth or growth spurt for most vocal tract structures between birth and approximately age 18 months; (b) the growth pattern of the various vocal tract structures varies according to its region (anterior, posterior, or combined) and orientation of growth (horizontal, vertical, or combined), wherein anterior structures appear to have a neural growth curve, posterior structures have a somatic growth curve, and structures/measurements encompassing both anterior and posterior regions—such as vocal tract length—have a combined or intermediate neural and somatic growth pattern as defined by Scammon (1930); and (c) the relational growth of the different vocal tract structures with vocal tract length changes during the course of development as a function of structure orientation (horizontal/vertical). These findings, followed by implications for speech acoustics and methodological issues, are discussed below.

The findings described above support the documented fact that growth or development does not advance in a linear fashion, but rather involves one or more periods of rapid growth or growth spurts (Gollin, 1981). As seen in Figs. 4 to 11, all the vocal tract structures examined exhibit a consistent trend of growth with no sexual dimorphism during the first 6 years of life, and a period of significant rapid or accelerated growth during early childhood, typically between birth and approximately age 18 months. See Table I for the breakpoints (brk.—age where growth rate changes) of specific structures as calculated by the broken line growth curve model. In general, the various vocal tract structures appear to follow the neural and/or the somatic growth curves as defined by Scammon (1930). The neural growth curve is characterized by a period of extremely rapid growth following birth until some variable time in early childhood where the structure is 2/3 of its adult size, followed by a period of very slow growth until maturity. The somatic growth curve is similar to the neural growth curve in having a phase of very rapid growth following birth and during infancy, but at the end of this rapid growth period, the structure is barely over a quarter of its adult size. The rapid growth period is then followed by an interval of regular but slow growth in early and middle childhood, then a period of rapid growth during puberty, and finally a period of slow but steady growth until early maturity. Figures 4 to 11 indicate that generally the growth of structures that are in the horizontal plane, such as the hard palate, follows a neural growth curve. For example, as seen in Fig. 9, the hard palate has an accelerated growth period from age 2 weeks to age 24 months, at which time it has reached 84% of its adult size. In contrast, the growth of structures that are in the vertical plane, such as the soft palate and laryngeal descent, follows a somatic growth curve. Furthermore, structures that are in both the horizontal and vertical planes, such as vocal tract length and tongue length, follow a combined or intermediate, neural and somatic growth curve. As noted in the Results section, the differences in growth between these three regions/orientations are significant. Although the available data in the current study are limited up to age 6 years 9 months and adults, these statements on type of growth curve are substantiated by examining the measures of the various structures at around age 18 months, and determining their percentage of the mature adult size. Differences in growth trajectories of vocal tract structures where the growth rates of the vertical and the horizontal portions of the vocal tract are different are also reported by Lieberman *et al.* (1999, 2001). The finding of accelerated growth during early childhood, particularly for vocal tract length, has implications for speech acoustics that are discussed below.

The ordering of the means reported in Table II—for both pre- and postbreakpoint segments (initial and final slopes)—reflects that combined (anterior and posterior) structures have the largest growth followed by posterior structures, and last by anterior structures for both the prebreakpoint and postbreakpoint segments. This order of growth was expected since the combined structures have larger measurements than the anterior or posterior structures alone because they include both anterior/horizontal and posterior/vertical regions/orientations. The posterior/vertical mean was also expected to exceed the anterior/horizontal mean since most anatomic restructuring—specifically laryngeal and hyoid descent—is reported to occur in the posterior or pharyngeal region where growth is predominantly in the vertical dimension. Thus, there is significantly more growth in the vertical dimension that in the horizontal dimension for both prebreakpoint and postbreakpoint segments.

Comparison of slope terms b (prebreakpoint segment) and slope terms c (postbreakpoint segment) in Table I, shows that the various vocal tract structures, or measures within a structure, have different growth rates that vary as a function of age but not gender. Consequently, it is to be expected that the relational growth of each of those structures with vocal tract length changes during the course of development (see Fig. 12). Based on knowledge of anatomic restructuring of the vocal tract (descent of the larynx and tongue), and the above finding on significant main effect for region/orientation in the nested ANOVA of pediatric pre- and postbreakpoint slopes, where comparison of the means in Table II indicates the growth of posterior structures to exceed the growth of anterior structures for both prebreakpoint and postbreakpoint segment (all pairwise differences significant), we expected the relational growth of the posterior structures (such as hyoid descent, laryngeal descent, and mandibular depth—structures with growth in the vertical dimension) with vocal tract length to exceed the relational growth of the anterior structures (such as palate length and mandibular length—structures with growth in the horizontal plane). Indeed, comparisons of the structures ordered according to percent variability (r-squared) in decreasing order (as is the case for peds I in Fig. 12), while taking into account the magnitude of percent variability, for each of the three age groups (peds I, peds II, and adults) indicate that although the relational growth of the different vocal tract structures with vocal tract length changes as a function of age, the relational growth of the posterior structures with vocal tract length is ongoing for all age groups. However, during the first 18 months of life (peds I group), there is almost as much associated growth of the anterior structures in the horizontal plane with vocal tract length as there is of posterior structures in the vertical plane with vocal tract length. For example, Fig. 12 shows that for peds I the first largest (82%) percent variability is from pharyngeal length—a posterior structure in the vertical dimension—and the sixth largest (58%) percent variability is from hard-palate length—an anterior structure in the horizontal dimension. After age 18 months, in general, the relational growth of posterior structures exceeds that of the anterior structures (i.e., growth is predominantly in the vertical dimension). For example, the third largest (57%) percent variability is from pharyngeal length, and the last (0.01%) percent variability is from hard-palate length. Such growth is also more pronounced for the adults' group. Thus, between the age of 6 years 9 months and adulthood, where the various vocal tract structures reach their mature size, the growth of all the different vocal tract structures persist, particularly for structures in the posterior region of the vocal tract. Fitch and Giedd's (1999) findings on vocal tract length using MRI indicate that growth in the posterior region of the vocal tract occurs predominantly during adolescence, particularly in males.

B. Acoustic implications

The current data on anatomic growth of the vocal tract structures provide an important first step towards exploring anatomic–acoustic interdependencies, that is, relating anatomic growth patterns to developmental changes in speech acoustics. The relevance of the anatomic findings in this report of an early period of accelerated growth of all vocal tract structures, including vocal tract length, and the absence of sexual dimorphism are discussed below with special consideration given to current knowledge of developmental changes in speech acoustics. The three major areas in speech acoustics discussed are (a) anticipated decrease in formant frequency as vocal tract length increases (Fant, 1960); (b) discriminable sex differences in speech acoustics by age 4; and (c) variability of the acoustic signal during development.

As the vocal tract develops, its acoustic properties change (Fant, 1960). Specifically, as age increases and the vocal tract lengthens, formant frequencies decrease. This decrease is typically attributed to increases in vocal tract length. However, during the first 2 years of life, there is evidence that the average formant frequencies remain unchanged, i.e., do not decrease, though there is an increase in the range of formant values (dispersion) (Buhr, 1980; Gilbert, Robb and Chen, 1997; Kent and Murray, 1982; Robb, Chen, and Gilbert, 1997; Stathopoulos, 1995). The anatomic implication of such acoustic findings is that there would be little or no expected change in vocal tract length during the first 2 years of life. However, as seen in Fig. 4, vocal tract length increases by 1.5 to 2 cm during this time period. Robb *et al.* (1997) attributed the lack of decrease in formant values during the first 2 years of life to developmental changes in anatomy that involve a more complex reconfiguration than a simple lengthening process. They also attributed the dispersion of formant frequencies to a larger vocal tract that allows for greater variability of tongue movement. Thus, there is an apparent need to supplement findings from the sagittal plane with data from multiple planes to gain a thorough understanding of the anatomic changes that the developing vocal tract and its component structures undergo so as to better understand acoustic–anatomic interdependencies. In other words, anatomic measurements should include changes in size (such as length and width) as well as changes in shape and configuration (such as area and volume). Such knowledge, in addition to assessing the role that anatomic growth plays in developmental changes in speech acoustics, would also lay the necessary normative foundation for the study of atypical growth patterns to determine how structural differences may contribute toward early neuromotor problems.

A detailed multidimensional understanding of the anatomic changes in supralaryngeal region that occur during development should, furthermore, lay the biological foundation for the perceived sex differences in speech acoustics. Despite the absence of sexual dimorphism in vocal tract structures and vocal tract length—measured in the sagittal plane—there are differences in formant frequencies between preadolescent boys and girls where boys as young as 4 years old have vowel formant frequencies that are lower than those of girls (Perry, Ohde, and Ashmead, 2001; Whiteside and Hodgson, 2000). This has been attributed to boys having a larger vocal tract than girls. Such differences in formant frequencies between boys and girls are present even when physical measurements such as body height and weight are taken into account since vocal tract length correlates with body dimensions (Fitch and Giedd, 1999). Thus male/female differences in formant frequencies before age 10 may be due to anatomical and/or articulatory sources other than vocal tract length. However, such conclusions based on acoustic changes are inferential and nonspecific, and again point to the need to have detailed understanding of the anatomic changes in the oral and pharyngeal regions that occur during development. Of particular interest are changes in the pharyngeal region, since most of the sex differences in adult speech acoustics have been attributed to differences in the pharyngeal region (Fant, 1966). Though not replicated here, King (1952), using x-ray cephalometry, has reported sex differences in pharyngeal length by the age of 1 where males have a longer pharyngeal length than females. King, however, defined pharyngeal length as a vertical measurement from the hard palate to the hyoid bone, which is only a portion of the actual naso-oro-pharyngeal length. Thus, a thorough investigation of developmental changes in the naso-oro-pharyngeal region is warranted using advanced imaging technology to assess changes in size (such as length and breadth) and volume of the pharynx. Such anatomic examination of sex-related differences in the growth of the front and back cavities may also help address the problem of the scaling of formant patterns as discussed by Kent (1976) and Goldstein (1980) where the uniform axial growth of the vocal tract is in question (Fant, 1966).

Having a detailed account of the biological changes in vocal tract anatomy, specifically identifying the growth pattern across development—including all periods of accelerated growth—would also promote our understanding of the anatomic bases of motor adjustments in speech development. A common interpretation made regarding motor development from acoustic and physiologic studies is that the high degree of variability that is observed in children's performance reflects the developing neuromuscular control or speech motor control whereby variability decreases as age increases (Eguchi and Hirsh, 1969; Tingley and Allen, 1975; Smith, Sugarman, and Long, 1983; Smith, 1994; Kent, 1976, 1992; Kent and Forner, 1980; Sharkey and Folkins, 1985; Lee *et al.*, 1999; Walsh and Smith, 2002; Wohlert and Smith, 2002). However, the assumption that variability is a direct measure of the maturation of the neural processes in speech motor control can be questioned. The variability measures are taken while there is ongoing anatomic growth including increases in size and changes in shape that alter the relative position of the various structures. Interestingly, as anatomic growth begins to decelerate after the first few years of life, so does variability. Thus, in addition to neural maturation, variability may reflect other developmental aspects, such as anatomic growth. At the least, it is necessary to consider several sources of variability in speech movements, including physical growth and remodeling of individual structures.

C. Other ramifications

Aside from using anatomic growth data to relate anatomic development to changes in speech acoustics, such data can also be used toward: gaining an appreciation of the simultaneous changes that the various vocal tract structures undergo while relating it to changes of the composite head and face structures (Vorperian *et al.*, 1999; Vorperian, 2000); developing infant and young child specific models of the developing vocal tract such as neural network models (Callan *et al.*, 2000); advancing statistical models of the developing vocal tract; and programming dynamic articulatory models of the developing vocal tract that have computer codes to make predictions regarding the acoustic formant space (Milenkovic, 1998; Milenkovic and Milenkovic, 1998). Such efforts would be instrumental in understanding how differential rates of growth of structures during development effect vocal tract geometry and in turn determine the articulatory space, i.e., production models specific to infants and young children. Such efforts will also help delineate anatomic versus motor contributions towards changes in acoustic output of the vocal tract.

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