Research Article

Kinematic Measurements of the Vocal-Fold Displacement Waveform in Typical Children and Adult Populations: Quantification of High-Speed Endoscopic Videos

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Purpose: This article presents a quantitative method for assessing instantaneous and average lateral vocal-fold motion from high-speed digital imaging, with a focus on developmental changes in vocal-fold kinematics during childhood.

Method: Vocal-fold vibrations were analyzed for 28 children (aged 5–11 years) and 28 adults (aged 21–45 years) without voice disorders. The following kinematic features were analyzed from the vocal-fold displacement waveforms: relative velocity-based features (normalized average and peak opening and closing velocities), relative acceleration-based features (normalized peak opening and closing accelerations), speed quotient, and normalized peak displacement.

Results: Children exhibited significantly larger normalized peak displacements, normalized average and peak opening

velocities, normalized average and peak closing velocities, peak opening and closing accelerations, and speed quotient compared to adult women. Values of normalized average closing velocity and speed quotient were higher in children compared to adult men.

Conclusions: When compared to adult men, developing children typically have higher estimates of kinematic features related to normalized displacement and its derivatives. In most cases, the kinematic features of children are closer to those of adult men than adult women. Even though boys experience greater changes in glottal length and pitch as they mature, results indicate that girls experience greater changes in kinematic features compared to boys.

The prevalence of hoarseness among school-age children ranges from 0.12% (McKinnon, McLeod, & Reilly, 2007) to 15.80% (Kallvik, Lindström, Holmqvist, Lindman, & Simberg, 2014). Early identification of lesion formation is dependent upon direct assessment of structure and function, on the basis of endoscopic visualization of the vocal folds. However, concepts and models of vocal-fold vibratory changes associated with normal and disordered phonation in children are not completely understood. Data on vocal-fold motion from adults are valuable but cannot be used for direct clinical analysis of vibratory motion in children, because laryngeal anatomy and structures in the pediatric population differ considerably from those of adults. The vocal folds in children are not only small (Hirano,

Kurita, & Nakashima, 1983; Kahane, 1982) but also different in terms of the histological composition of the layered vocal-fold structure: Children have a less developed vocal-fold layered structure than adults (Hartnick, Rehbar, & Prasad, 2005; Hirano et al., 1983; Sato, Hirano, & Nakashima, 2001). Since vibratory functions are largely determined by the length of the membranous portion and the stiffness resulting from vocal-fold muscle (Titze, 1994b), it appears reasonable to hypothesize that the resulting vibratory kinematics from the immature vocal-fold structure would differ considerably in children compared to adults.

For early identification and clinical assessment of disordered vibratory motion in the pediatric population, it is critical to establish a concept of normal vocal-fold vibratory motion in children for habitual phonation. Limited investigations on direct assessment of vibratory function in children, on the basis of qualitative (visual frame-by-frame analysis) and quantitative (glottal-area waveform and phonovibrogram) analysis of high-speed video, have established functional differences in some aspects of glottal-cycle characteristics compared to adults. Qualitative analysis of glottal-cycle montage has demonstrated a predominantly open phase

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of the glottal cycle and higher incidence of posterior phonatory gap in children during habitual phonation (Patel, Dixon, Richmond, & Donohue, 2012). Quantitative analysis of glottal-area waveform using glottal quotients has revealed that children have a greater opening-phase duration of the glottal cycle compared to adults, as indicated by the larger values of speed index and asymmetry quotient (Patel, Dubrovskiy, & Döllinger, 2014b). Analysis of phonovibrograms, which use the degree of angle to indicate the time-dependent course of the vocal fold opening and closing, also showed longer opening-phase durations of the glottal cycle in typically developing children compared to adults (Döllinger, Dubrovskiy, & Patel, 2012).

Additionally, analysis of glottal-area derivatives has revealed that vibratory motion in children is characterized by a lower value of the maximum area declination rate and a high value of amplitude quotient; these differences are indicative of greater relative peak closing velocity and reduced stiffness compared to adults (Patel et al., 2014b). Vibratory motion in children is also characterized by high amplitude and time aperiodicities compared to adults but is similar to adults in terms of spatial and phase symmetry (Patel et al., 2014a). These limited investigations thus far have revealed that vocal-fold vibrations in children are not scaled-down versions of adult vibrations but are functionally different from those of adults. Much research remains to be conducted in terms of characterizing the motion of vocal-fold tissue in terms of velocity and acceleration properties.

Kinematics of first and second derivatives of tissue motion have the potential not only to characterize normal vocal-fold dynamics comprehensively (Woo, 1996) but also to systematically depict disorder-specific vibratory characteristics that are useful for both understanding the clinical pathophysiology of various voice disorders and measuring voice therapy outcomes (Lohscheller & Eysholdt, 2008; Noordzij & Woo, 2000; Patel, Pickering, Stemple, & Donohue, 2012). Kinematics of direct tissue motion on the basis of velocity and acceleration profiles in order to characterize vibratory dynamics have been underutilized in adult studies and are, to the best of our knowledge, nonexistent in studies of children. One reason is that the cycle-to-cycle vocal-fold motion is not directly captured with popular modalities, such as stroboscopy. In addition, even with modalities such as high-speed digital imaging and videokymography, which capture multiple frames per phonation cycle, special calibration techniques and/or light projectors are needed to estimate true size measurements and velocities (Larsson & Hertegård, 2004; Patel, Donohue, Johnson, & Archer, 2011; Patel, Donohue, Lau, & Unnikrishnan, 2013; Wurzbacher et al., 2008). Laser endoscopy coupled with high-speed digital imaging and/or videokymography is the ultimate goal for clinical quantification of vibratory dynamics and lesion size. However, laser endoscopy in its current state increases the size and complexity of the endoscope, which is especially problematic in the assessment of pediatric vocal-fold motion. Moreover, endoscopes with laser attachments are currently not commercially available for routine clinical use.

High-speed digital imaging with increased temporal resolution relative to stroboscopy appears to be ideal for visual qualitative (Patel, Dixon, et al., 2012) and quantitative (Döllinger et al., 2012; Patel et al., 2011, 2014a, 2014b) analysis of vocal-fold vibratory function in the pediatric population. Visual frame-by-frame analysis of high-speed video is time consuming and hence extremely limiting. Quantitative assessments of vibratory motion derived from high-speed imaging traditionally have examined the time-varying glottal-area waveform in terms of glottal cycle quotients (e.g., open quotient, speed quotient; Timcke, von Leden, & Moore, 1958; Yan, Ahmad, Kunduk, & Bless, 2005). First-derivatives of the glottal-area waveform have been investigated in terms of amplitude quotient and maximum area declination rate by very few studies (Bohr, Kraeck, Eysholdt, Ziethe, & Döllinger, 2013; Patel et al., 2014b). The derivatives of maximum area declination rate and amplitude quotient provide indirect information regarding the vocal-fold closing velocity and tissue pliability, respectively. The analyses of time-varying glottal-area waveform parameters, though useful, fail to provide vibratory details of regions of interest along the vocal fold. In a study of 30 healthy male and 30 healthy female subjects, Lohscheller, Švec, and Döllinger (2013) demonstrated that the open quotient and speed quotient were markedly different for the midmembranous portion compared to the anterior and posterior margins of the vocal folds. This level of detail is critical because many vocal-fold lesions are not symmetric and are known to affect vocal-fold vibrations differently on the basis of their size, extent, and location along the glottal length.

Alternatively, digital kymographs have been used to extract lateral displacement waveforms from specific regions of interest to derive characteristics of vibratory motion from high-speed video (Bonilha, Deliyski, & Gerlach, 2008; Lohscheller et al., 2013; Mehta, Deliyski, Quatieri, & Hillman, 2011), while phonovibrograms have been used to comprehensively describe anterior/posterior and left/right vocal-fold motion across time (Lohscheller & Eysholdt, 2008; Lohscheller, Eysholdt, Toy, & Döllinger, 2008). The displacement waveforms derived from digital kymographs have been used to extract glottal quotients (Lohscheller et al., 2013) and glottal-cycle periodicity and symmetry measures (Bonilha et al., 2008; Mehta et al., 2011) similar to those extracted from the glottal-area waveform. Lohscheller and Eysholdt (2008) reported the use of velocity and acceleration derivatives of vocal-fold edges where the entire vibratory motion can be comprehensively visualized pictorially in an image called a phonovibrogram. The pictorial depiction of a phonovibrogram, however, is nonintuitive because it splits the glottis in such a way that the movement of the left vocal fold is displayed on the top screen, whereas the right vocal-fold motion is displayed on the bottom screen, with the posterior glottis in the center of the screen. Hence, phonovibrogram analysis, though comprehensive, has not gained widespread use for clinical assessment thus far.

This study examines the question of direct characterization of vocal-fold vibratory motion differences between

children and adults, in terms of features related to velocity and acceleration, by introducing kinematic features that quantify the instantaneous and average dynamics of the opening and closing phases of the glottal cycle. Relative velocity and acceleration trajectories were derived from the displacement waveforms that track the lateral motion of the vocal folds. The waveforms estimated from the pixel positions are typically influenced by the variations in image resolution and camera distances. The variations in pixel distance were removed by normalizing the displacement waveform with the glottal length in pixels. In addition, the obvious timescale differences between the cycle periods of the populations (children and adult) were removed by normalizing the time axis by the glottal period. These normalization steps remove the numerical influence of glottal length and pitch from the motion characterization. The features from these scaled waveforms, therefore, reflect motion dynamics that typically influence the qualitative impression of the video. The units of displacement were measured in terms of the glottal lengths, and the units of velocity were in glottal lengths per cycle. In order to distinguish these features from actual displacement and velocity, the terms *normalized displacement* and *normalized velocity* are used.

While the displacement waveform and its derivatives are a subset of the information provided in the phonovibrogram, this work applies additional processing to the displacement waveform to reduce variability from rounding positions to the nearest pixel and time points to the nearest sample. Reduction of these errors is especially important when comparing populations with a wide range of frequencies and vocal-fold displacements. Higher frequencies common in the pediatric population result in fewer samples per glottal cycle than the lower frequencies in the adult population. The resulting error from rounding glottal opening or closing time points to the nearest frame (sample) can be 2 to 3 times higher for the pediatric population compared to the adult population. Likewise, the smaller absolute displacement (Patel et al., 2011) of the pediatric vocal fold can lead to fewer pixels over the open phase, resulting in a greater percentage of displacement error in measuring the amplitude displacement. The quantization differences from rounding errors of the pixel positions were minimized through a smoothing process called denoising (Coifman & Donoho, 1995), and estimations of critical time points (peak displacement, opening, and closing) were enhanced through extrapolation and interpolation (Unnikrishnan, Donohue, & Patel, 2012; Unser, Aldroubi, & Eden, 1993).

The normalized velocity and acceleration features used in this article could be interpreted as the relative distribution of velocity (i.e., directly related to energy) and acceleration (i.e., directly related to force) over the phonation cycle rather than the absolute velocities and forces. The normalized velocities were calculated at various time points over the opening and closing intervals to characterize the glottal-cycle dynamics. While the closing phase of the glottal cycle is more important in terms of sound production and is of greater clinical interest (Holmberg, Hillman, &

Perkell, 1988; Scherer & Titze, 1982), similar features for the opening phase were examined for characterizing the symmetry of motion between the opening and closing phases. In addition, the speed quotient (Timcke et al., 1958) was computed as a feature for comparison.

The kinematic features introduced here allow for analyzing the opening and closing phases separately as well as quantifying the instantaneous dynamics from the displacement waveform. These features are peak normalized displacement, normalized peak and average opening velocities, normalized peak and average closing velocities, normalized peak closing acceleration, and normalized peak opening acceleration to characterize vibratory motion in children during modal phonation (typical pitch and loudness). In order to examine the influence of various voice disorders on the kinematic features, it is clinically critical to know normative values and the range of vibratory behavior in terms of peak displacement, velocity, and acceleration-based measures for modal phonation.

The aim of this prospective study is to examine the nature of age-related differences in kinematic features on the basis of relative displacements, velocities, and accelerations of vibratory motion between children and adults. Using kinematic features of normalized displacement, normalized velocity, and normalized acceleration, the following questions were addressed: (a) How similar or distinct are children's vibratory patterns compared with adult men's and women's when the scaling from pitch and glottal length is accounted for? (b) Do children have a greater speed quotient compared to the adults, and do both the opening and closing phases contribute equally to this difference? (c) Do children have greater normalized peak displacement (amplitude-to-length ratio) compared to the adults?

Method

Participants

A total of 54 children (ages 5–11 years) and 39 adults (ages 21–45 years) were recruited by the University of Kentucky's Vocal Physiology and Imaging Laboratory after signing consent and assent forms approved by the institutional review board. Children and adults were included in the study if they had no negative histories of vocal pathology, were not professional voice users, and were judged to have perceptually normal voices by a certified speech-language pathologist specializing in voice disorders. Children experiencing puberty were excluded from the study, as were adults with a history of smoking.

Data from 19 children and one adult were not collected due to heightened gag reflexes. Hence, high-speed images were obtained from a total of 35 children and 38 adults. Seven additional children could not be included in the study because the recorded sample lacked 30 cycles of steady phonation at normal pitch and loudness. A 30-cycle duration of steady phonation was short enough to be easily identified in most subjects and long enough to provide feature estimates representative of the phonation dynamics.

Data from 10 adults were excluded due to failure of the image processing algorithm to reliably detect the vocal-fold margins as determined by human verification. Tracking failures primarily resulted from spurious edges from secondary shadows and light variations in the subglottis. For these reasons, the study included data from 28 children (girls = 12, boys = 16) and 28 adults (women = 17, men = 11).

High-Speed Digital Imaging

The participants' task was to sustain phonation of the vowel /i/ at a typical pitch and loudness while high-speed images were recorded. The recordings were acquired with a digital grayscale Pentax high-speed system (model 9710) with a sampling rate of 4,000 frames/s and a spatial resolution of 512×256 pixels for a maximum duration of 4.094 s. The camera was coupled to a 70° Pentax digital endoscope with a xenon light source of 300 W. Topical anesthetic was not used during the examinations. The participants were directed to phonate at their normal speaking loudness, and the sound pressure wave was recorded on a linear scale using a collar microphone synchronized with the high-speed video.

Data Segmentation

Image segmentation and parameter estimation were performed by applying a customized software tool developed at the University of Kentucky Vocal Physiology and Imaging Laboratory in conjunction with the Center of Visualization, College of Engineering. The pitch trace, root-mean-square contour, and wideband spectrogram on the TF32 acoustic analysis software (Milenkovic, 2003) was used to guide the segmentation of steady-state phonation. The acoustic tracings were examined visually to ensure stability of phonation, and then a quantitative analysis verified that the signal did not change more than 20 Hz in a 20-ms window, which is an empirical definition used for steady-state phonation (Kent et al., 1989). For each subject, a steady-state phonation segment was selected and analyzed.

Edge Detection and Displacement Estimation

The custom-developed vocal-fold contour detection algorithm consists of three steps: (1) region-of-interest tracking, (2) robust intensity thresholding, and (3) displacement estimation (Unnikrishnan et al., 2012). The semiautomatic algorithm presented a human observer with the captured edges overlaid on the original video for validation. If the edges were not properly tracked, the observer could adjust a parameter governing the size of the region of interest and rerun the tracking algorithm. All other parameters related to edge detection were estimated automatically through adaptive and iterative procedures. The accuracy of the custom-developed automatic algorithm is high, with subpixel mean difference (range = 0.45–0.92 pixels) and standard deviation (range = 0.01–0.08 pixels) comparable to the edges selected by a human expert (Unnikrishnan et al., 2012). The vocal-fold displacements were estimated

from the midmembranous portion of the vocal folds (see Figure 1), since this is the region where maximum changes in the lateral motion are evidenced compared to the anterior and posterior margins (Lohscheller et al., 2013; Timcke et al., 1958). Displacements of the left and right vocal folds were computed separately on the basis of the midline glottal axis. The displacements were enhanced over the pixel positions at the video frame rate through denoising and interpolation/extrapolation. The denoising operation reduces the effects of low-level quantization or rounding error from the pixelation and results in a smoother trajectory consistent with quasiperiodic motion of the phonating vocal fold. The interpolation and extrapolation are polynomial based (Unser et al., 1993) and more consistently determine the critical time points, such as the peak displacement, opening, and closing times, beyond the limited sampling times of the frame rate (Unnikrishnan et al., 2012).

Kinematic Feature Extraction

Kinematic features on the basis of normalized displacements, normalized velocities, and normalized accelerations were estimated from 30 consecutive cycles of sustained oscillation, where the timescale for each cycle was normalized; displacements were normalized by the glottal length, which results in a geometric property of the fold displacement. Earlier attempts without this normalization on per-cycle features resulted in increased variability from pixel scales and wide timescale variation on each cycle, obscuring the population-based differences in vibratory motion.

For the participants in this study, the mean fundamental phonation frequency was 210.10 Hz ($SD = 18.21$) for women, 141.20 Hz ($SD = 17.24$) for men, 256.38 Hz ($SD = 28.57$) for boys, and 261.78 Hz ($SD = 30.01$) for girls. These large differences in pitch would influence features derived from the timescales and obscure other differences

Figure 1. Extracted contours with median line and projection for amplitude.

in vibratory dynamics. Scaling the time axis to normalize the pitch removes between-groups differences related to pitch and results in phase quantities (per cycle units) that describe dynamics relative to the glottal cycle. Therefore, kinematic features used in this analysis eliminate the two most obvious variations between groups—glottal length and pitch—to bring out more subtle aspects of the kinematics, such as energy distribution over the cycle (normalized velocity- and acceleration-based features) and relative displacement of the tissue.

Children and women were on average 2.57 and 1.05 dB louder than men, respectively. The intragroup standard deviations were 2.98 (children), 2.65 (women), and 2.08 dB (men), which indicates that average loudness values were within one standard deviation and were not a major influence on the features.

A total of eight kinematic features were computed to comprehensively quantify the relationships between the opening and closing phases of a glottal cycle. The mean of each feature was computed over all cycles, along with its standard deviation, to assess the cycle-to-cycle variability over the sustained phonation. Figure 2 illustrates the salient time points used to estimate the features. The time point at which the vocal folds begin to open (beginning of the opening phase) for the m th cycle is denoted $t_{o,m}$, whereas the time point where the vocal folds close (ending of the closing phase) is denoted $t_{c,m}$. Maximum vocal-fold openings for the left and right vocal folds are indicated by $t_{pl,m}$ and $t_{pr,m}$, respectively. The examples of peak (instantaneous) and average features relative to the glottal waveform and its derivatives are graphically represented in Figure 3.

Figure 2. Schematic of vocal-fold motion illustrating salient time instances in a glottal displacement waveform. The time point at which the vocal folds begin to open (beginning of the opening phase) for the m th cycle is denoted $t_{o,m}$, whereas the time point where the vocal folds close (ending of the closing phase) is denoted $t_{c,m}$. Maximum vocal-fold openings for the left and right vocal folds are indicated by $t_{pl,m}$ and $t_{pr,m}$, respectively.

All features were computed for left and right vocal folds separately in each cycle. The maximum feature value from both the vocal folds in each cycle was used for averaging over all 30 cycles to compute the features for the analysis. For a generic feature this operation is explicitly denoted as

$$F_{avg} = \frac{1}{M} \sum_{m=1}^M \max\{F_l[m], F_r[m]\}, \quad (1)$$

where the subscripts indicate left or right, F represents the feature value, M is the number of cycles, and F_{avg} is the summary feature value. For all cases presented in this analysis, $M = 30$. In order to characterize the cycle-to-cycle variation of each subject, the standard deviation for each feature was computed by

$$F_{SD} = \sqrt{\frac{1}{M-1} \sum_{m=1}^M (\max\{F_l[m], F_r[m]\} - F_{avg})^2}. \quad (2)$$

For simplicity, only the left vocal-fold features are presented in the following descriptions. The definitions are analogous for the right fold.

Kinematic feature representing geometric displacement. Normalized peak displacement (d^p) represents the maximum lateral excursion of the vocal fold from the glottal midline, normalized by the glottal length. The normalized peak displacement for the left fold was computed by

$$d_l^p[m] = \max\{L(t)\} \text{ for } t_{o,m} \leq t < t_{c,m}, \quad (3)$$

where $L(t)$ is the lateral displacement normalized by the glottal length as illustrated in Figure 1, and time points $t_{o,m}$ and $t_{c,m}$ represent the opening and closing point of the m th cycle, respectively (see Figure 2). The normalized displacement differs from absolute displacement in that it characterizes the relative portion of the vocal fold displaced rather than the actual distance. Therefore, this feature is proportional to the percentage of tissue displaced relative to the glottal length during phonation. As the folds lengthen and stiffen during the maturation process, this feature is expected to reduce and could be useful in quantifying the vocal-fold maturation process.

Kinematic features representing velocity. Normalized velocities provide information regarding the energy distribution over the phases of the glottal cycle, where dynamics for the opening and closing phases can be observed separately. Velocity distributions can be characterized by the average and peak velocities in the opening and closing phases. A change in velocity occurs when the fold undergoes force or acceleration (Titze, 1988; Young & Freedman, 2013). The greatest changes typically occur at the beginning and end of each glottal-cycle phase. If the velocity remains constant after opening to the peak lateral displacement, the peak and average velocities will remain the same. Greater

Figure 3. Plot of instantaneous displacement, normalized velocity, and normalized acceleration of left vocal-fold motion, illustrating normalized peak displacement, normalized average and peak opening velocities, normalized average and peak closing velocities, and normalized peak opening and closing accelerations.

differences between the peak and average velocities imply greater acceleration during that portion of the glottal cycle (Young & Freedman, 2013).

The comparisons between average normalized velocities in the opening and closing phases are useful for characterizing the kinematic symmetry and distribution of energy between the two phases. Therefore, features related to the normalized velocities were extracted and analyzed over opening and closing phases of the glottal cycle. These include the normalized average opening velocity (V_o), normalized peak opening velocity (V_o^p), normalized average closing velocity (V_c), and normalized peak closing velocity (V_c^p). The normalized average opening velocity (V_o) for the left vocal fold was computed by

$$V_{o,l}[m] = \frac{L(t_{pl,m}) - L(t_{o,m})}{t_{pl,m} - t_{o,m}}, \quad (4)$$

where $t_{pl,m}$ and $t_{o,m}$ represent the peak opening and open point for left vocal fold in the m th cycle (see Figure 2). The normalized peak opening velocity (V_o^p), which is the

maximum displacement gradient during the opening phase, was computed by

$$V_{o,l}^p[m] = \max\{v_l(t)\} \text{ for } t_{o,m} \leq t < t_{pl,m}, \quad (5)$$

where $v_l(t)$ is the instantaneous velocity of the left vocal fold. Analogously, the normalized average closing velocity (V_c) for the left vocal fold was given by

$$V_{c,l}[m] = \frac{L(t_{c,m}) - L(t_{pl,m})}{t_{c,m} - t_{pl,m}}, \quad (6)$$

where $t_{pl,m}$ and $t_{c,m}$ are the peak opening and close points for the left focal fold in the m th cycle. The normalized peak closing velocity (V_c^p) is the minimum displacement gradient value during the closing phase. The V_c^p for the left vocal fold was computed by

$$V_{c,l}^p[m] = \min\{v_l(t)\} \text{ for } t_{pl,m} \leq t < t_{c,m}. \quad (7)$$

It is expected that as the vibratory motion matures with smaller displacement-to-glottal-length ratios, the vocal fold will exhibit a more linear elasticity with an even balance between the energies in opening and closing phases (Chang, Tian, Luo, Doyle, & Rousseau, 2013).

Kinematic features representing acceleration. Normalized accelerations were computed directly from the normalized velocity gradients. The normalized peak acceleration during the trajectory indicates when the folds undergo the greatest relative force along the motion axis (Titze, 1994a), which is expected at the start and end of the open phase and at peak displacement (maximum open phase). The features of normalized peak opening acceleration (A_{ol}^p) and normalized peak closing acceleration (A_{cl}^p) were used to quantify the kinematic acceleration distribution over the glottal cycle, computed by

$$A_{ol}^p[m] = \max\{a_l(t)\} \quad \text{for } t_{o,m} \leq t < t_{pl,m}, \quad (8)$$

where $a_l(t)$ denotes the double derivative of the left vocal-fold displacement waveform, and $t_{o,m}$ and $t_{pl,m}$ are the peak open and peak opening points for the left focal fold in the m th cycle. The normalized peak closing acceleration (A_{cl}^p) for the left vocal fold was computed by

$$A_{cl}^p[m] = \max\{a_l(t)\} \quad \text{for } t_{pl,m} \leq t < t_{c,m}, \quad (9)$$

where $a_l(t)$ denotes the double derivative of the left vocal-fold displacement waveform, and $t_{pl,m}$ and $t_{c,m}$ are the peak opening and close points for the left focal fold in the m th cycle. It is expected that the lack of stiffness for the immature fold would result in a higher concentration of acceleration at the glottal opening and closing events, where either the subglottal pressure or Bernoulli forces are typically the greatest (Laver, 1994).

Speed quotient. The speed quotient represents the time from the opening of the vocal fold to its peak lateral excursion divided by the time from the peak lateral excursion to the closing time (Timcke et al., 1958). It captures the degree of symmetry for the vocal-fold motion during the open phase for each cycle. For the left fold this was given by

$$S_l[m] = \frac{t_{pl,m} - t_{o,m}}{t_{c,m} - t_{pl,m}}, \quad (10)$$

where $t_{pl,m}$, $t_{c,m}$, and $t_{o,m}$ are the peak opening, close, and open points (respectively) for the left focal fold in the m th cycle. The feature of speed quotient has been used in other studies and is presented here for comparison. The normalized average velocities provide similar information, with the advantage of observing the individual opening and closing phases across subjects. The speed quotient is not affected by the length of the open phase, hence the portion of time for the opening and closing phases over the entire glottal cycle is not apparent like it is in the kinematic measure of normalized average velocities.

Statistical Analysis

A two-sample t test was used to compare the means and standard deviations between boys ($n = 16$) and girls ($n = 12$) aged 5–11 years. None of the variables or their standard deviations varied significantly between boys and girls; hence, for further statistical analysis, data from all children were combined for comparison to adults. A one-way analysis of variance (ANOVA) was used to compare the means and mean standard deviations among the three groups (men, women, and children). A step-down Bonferroni–Holmes procedure was used to determine the significance levels for the ANOVA. Post hoc comparison of the means and standard deviations relied on Fisher’s protected least significant difference procedure. Results were considered significant for $p \leq .05$ levels for the post hoc analysis. Effect size (ES) denotes the proportion of variance explained. All analyses were performed using SAS statistical software, Version 9.2, for PCs (SAS Institute, n.d.).

Results

A total of eight kinematic features were used to characterize the opening and closing phases of the glottal cycle across participant groups (women, men, and children). The F scores, p values, and effect sizes for the mean feature values computed over all cycles (Equation 1) are reported in Table 1, and the standard deviations over the 30-cycle segment (Equation 2) are reported in Table 2.

Vibratory Kinematic Differences Between Children and Adults

Results show that participant groups (women, men, and children) have statistically significant differences among them for all the features (see Table 1). The strongest effect sizes were those associated with closing-phase features, with almost twice the effect size as features for the corresponding opening-phase features.

The p levels were adjusted for multiple comparisons in the ANOVA. Pairwise comparison with the Fisher’s protected least significant difference revealed that compared to women, children had a significantly larger normalized peak displacement, $t(43) = 4.74$, $p < .001$, ES = .34; normalized average opening velocity, $t(43) = 3.19$, $p = .002$, ES = .19; normalized peak opening velocity, $t(43) = 2.99$, $p = .004$, ES = .17; normalized average closing velocity, $t(43) = 4.85$, $p < .001$, ES = .35; normalized peak closing velocity, $t(43) = 4.27$, $p < .001$, ES = .30; normalized peak opening acceleration, $t(43) = 2.96$, $p = .004$, ES = .17; normalized peak closing acceleration, $t(43) = 4.46$, $p < .001$, ES = .32; and speed quotient, $t(43) = 3.57$, $p < .001$, ES = .23 (see Figure 4). Compared to men, children had higher values of normalized average closing velocity, $t(37) = 2.51$, $p = .015$, ES = .15, and speed quotient, $t(37) = 3.04$, $p = .003$, ES = .20.

Variability was assessed with a between-subjects, one-way ANOVA, with the mean of the cycle-to-cycle standard deviations for each dependent variable compared

Table 1. Comparison of women, men, and children across the mean of the kinematic features using a one-way analysis of variance.

Dependent variable	Women (<i>n</i> = 17)	Men (<i>n</i> = 11)	Children (<i>n</i> = 28)	<i>F</i>	<i>p</i>	Effect size
	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)			
Normalized peak displacement (<i>d^P</i>)	0.087 (0.022)	0.122 (0.055)	0.144 (0.044)	11.266	<.001	.303
Normalized average opening velocity (<i>V_o</i>)	0.300 (0.077)	0.455 (0.155)	0.488 (0.222)	5.322	.008	.177
Normalized peak opening velocity (<i>V_o^P</i>)	0.455 (0.099)	0.755 (0.299)	0.707 (0.322)	5.699	.006	.188
Normalized average closing velocity (<i>V_c</i>)	0.299 (0.099)	0.404 (0.188)	0.566 (0.222)	12.255	<.001	.322
Normalized peak closing velocity (<i>V_c^P</i>)	0.433 (0.122)	0.722 (0.366)	0.811 (0.322)	9.299	.000	.266
Normalized peak opening acceleration (<i>A_o^P</i>)	101.155 (23.099)	163.088 (57.411)	151.122 (66.055)	5.799	.005	.188
Normalized peak closing acceleration (<i>A_c^P</i>)	98.877 (30.999)	148.511 (68.299)	180.909 (68.744)	9.955	.000	.277
Speed quotient (<i>S</i>)	1.122 (0.233)	1.136 (0.311)	1.566 (0.499)	8.344	.001	.244

Note. For the analysis, *dfs* = (2, 53).

across the three participant groups. There were statistically significant effects of participant group for standard deviations on two out of eight features (normalized average closing velocity and normalized peak closing acceleration; see Table 2). The *p* levels were adjusted for multiple comparisons in the ANOVA. Post hoc analysis with the Fisher's protected least significant difference revealed that compared to women, children exhibited significantly greater cycle-to-cycle variability in normalized average closing velocity, $t(43) = 3.72$, $p \leq .001$, *ES* = .23, and normalized peak closing acceleration, $t(43) = 3.55$, $p < .001$, *ES* = .23.

Vibratory Kinematic Differences Between Women and Men

Compared to men, women had significantly smaller normalized peak displacement, $t(26) = 2.15$, $p = .036$; normalized average opening velocity, $t(26) = -2.14$, $p = .037$; normalized peak opening velocity, $t(26) = -2.83$, $p = .007$; normalized peak closing velocity, $t(26) = -2.64$, $p = .011$; normalized peak opening acceleration, $t(26) = -2.92$, $p = .005$; and normalized peak closing acceleration, $t(26) = -2.15$, $p = .037$ (see Figure 5).

Discussion

This article reports a method of kinematic analysis to estimate normalized velocity- and acceleration-based

measures for characterizing the instantaneous and average dynamics of the opening and closing phases of the glottal cycle related to pediatric vocal-fold maturation. The findings from this study on the population groups suggest that mature oscillatory vocal-fold motion in children is not established by 11 years of age but refines during early development. The study findings provide the impression that vocal-fold movements of typically developing children are more similar to those of adult men than women. Several statistically significant findings contribute to this impression. Compared to women, children and men have greater normalized peak displacement, higher normalized average and peak opening velocities, increased normalized peak closing velocity and acceleration, and increased normalized peak opening acceleration.

It is well known that the size of the larynx and the vocal folds are smaller in children compared to adults (Hartnick et al., 2005; Hirano et al., 1983; Kahane, 1982). Investigation into the prepubertal gender differences in the dimensions of the laryngeal cartilages has revealed that the larynx in prepubertal girls is closer in size and weight to the larynx in women than it is to the larynx in boys (Kahane, 1978). In contrast to the size difference, data from the current study suggest that the kinematic trajectories derived from the normalized vocal-fold displacement waveform in children are comparable to those in men. Even though we did not include gender as a variable, it can be hypothesized that girls would undergo a greater change in the vibratory

Table 2. Comparison of women, men, and children across the standard deviation of the kinematic features using a one-way analysis of variance.

Dependent variable	Women (<i>n</i> = 17)	Men (<i>n</i> = 11)	Children (<i>n</i> = 28)	<i>F</i>	<i>p</i>	Effect size
	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)			
<i>SD</i> normalized peak displacement (<i>d^P</i>)	0.003 (0.003)	0.004 (0.003)	0.006 (0.003)	4.93	.011	.16
<i>SD</i> normalized average opening velocity (<i>V_o</i>)	0.019 (0.010)	0.023 (0.011)	0.028 (0.018)	1.74	.185	.06
<i>SD</i> normalized peak opening velocity (<i>V_o^P</i>)	0.049 (0.023)	0.087 (0.079)	0.071 (0.041)	2.44	.097	.08
<i>SD</i> normalized average closing velocity (<i>V_c</i>)	0.017 (0.007)	0.024 (0.014)	0.035 (0.021)	7.18	.002	.21
<i>SD</i> normalized peak closing velocity (<i>V_c^P</i>)	0.049 (0.029)	0.097 (0.077)	0.086 (0.053)	3.57	.035	.12
<i>SD</i> normalized peak opening acceleration (<i>A_o^P</i>)	17.755 (6.95)	28.676 (18.4)	26.909 (18.752)	2.19	.122	.08
<i>SD</i> normalized peak closing acceleration (<i>A_c^P</i>)	17.061 (8.985)	27.208 (17.45)	34.462 (18.366)	6.32	.003	.19
<i>SD</i> speed quotient (<i>S</i>)	0.072 (0.044)	0.077 (0.050)	0.120 (0.082)	3.45	.039	.12

Note. For the analysis, *dfs* = (2, 53).

Figure 4. Plot of instantaneous displacement and normalized velocity of left vocal-fold motion for (a) a woman, (b) a man, and (c) a child, illustrating higher normalized peak velocity and normalized peak-to-average velocity for the child.

kinematics to achieve the target developmental end point compared to boys, who undergo greater size changes. Women show the smallest normalized displacement, while both boys and girls have the largest normalized displacement, with no significant difference between the genders.

The smaller normalized displacement of women indicates that a lesser percentage of the fold tissue is being displaced. Boys, on the other hand, maintain the larger normalized displacement into adulthood while dropping dramatically in pitch. Additionally, the expected changes in kinematics could be due to the differential fiber composition in the cellular layered structure—especially of the ligament of the vocal folds—between girls and boys (Hartnick et al., 2005). However, the rate of growth of the differential fiber composition and the ligament in prepubertal girls and boys is not fully understood.

The results show that the closing-phase features have the strongest effect size, indicating more consistent behavior over the population compared to the opening-phase features. Children have the highest normalized average closing velocity compared to women and men. The normalized average closing velocity in children is 40% greater than that in men and 93% greater compared to women, indicating that children exhibit larger, if not similar, normalized kinematic trajectories compared to men. The kinematic results clearly show a greater percentage of energy concentrated in the closing phases for the developing folds compared to the opening phase. While the values of normalized peak closing velocity and normalized peak closing acceleration were highest in children, they were only statistically significant compared to women due to the stringent alpha level. The greater normalized peak closing velocity demonstrated here is consistent with the finding of increased maximum area declination rate shown by Patel et al. (2014b), who used glottal-area waveforms.

The property of larger kinematic trajectories is illustrated in Figure 4, which compares representative examples of the normalized displacement and relative normalized velocity profiles of a woman, a man, and a child. Overall, it is evident from Figure 4 that during the opening phase of the glottal cycle (outward movement), the normalized velocity is positive, whereas during the closing phase (inward movement), the normalized velocity is negative. The vibratory motion in the child (see Figure 4c) shows rapid and large changes in the normalized velocity profile for the opening and closing phases. The irregular velocity distribution in the pediatric vocal fold, especially during the closing phase of the glottal cycle, appears to be similar to that of the man (see Figure 4b) but with greater magnitude. The population results show that relative to the opening, the closing phases of the glottal cycle in children have larger normalized velocities, which could be attributed as characteristics of immature vocal-fold motion.

Findings from the normalized features suggest that the differences for maturing vocal folds are directly related to the cycle-to-cycle variability and distribution of energy over the phonation cycle. Absolute velocities and accelerations are not reflected in these numbers. The kinematic features presented here would have to be scaled by glottal lengths and pitch values to estimate absolute velocities. In the population groups studied, the average fundamental frequencies were 256, 210, and 141 Hz for children, women, and men, respectively. Patel et al. (2013) found average

Figure 5. Bar graphs summarizing the evaluated features across children, men, and women: (a) normalized peak displacement, (b) speed quotient, (c) normalized opening velocity, (d) normalized closing velocity, and (e) normalized acceleration. Population means are indicated numerically above each bar.

glottal lengths for children ($n = 5$), women ($n = 3$), and men ($n = 2$) that measured 6.4, 11.4, and 15 mm, respectively. If these are representative of the current population, then the scaling factors required to turn units into meters per second are approximately 1.6, 2.3, and 2.1 for children, women, and men, respectively. These numbers suggest that actual velocities of children and adults are similar (velocities for adults were about 30% higher), reducing the significance of the distinguishing features. While these inferences on actual velocity are based on applying average population values estimated from two-dimensional video (Deliyski et al., 2008), additional investigations of three-dimensional reconstruction of the glottis with laser endoscopy coupled with high-speed video are needed to conclusively assess actual velocities and their relationship to the normalized kinematic features in characterizing the maturing vibratory motion.

Children in this study also demonstrate increased cycle-to-cycle variability in normalized average closing velocity and normalized peak closing acceleration compared to women. This high variability suggests less stability of the closing phase of the glottal cycle in children compared to the opening phase. Spatiotemporal analysis of the opening and closing phases using the phonovibrogram analysis also demonstrates greater temporal variability in the closing phase compared to the opening phase in typically developing children (Döllinger et al., 2012). The high prevalence of larger posterior phonatory gaps (Patel, Dixon, et al., 2012) in children may also contribute to increased instability of the closing phase compared to adults.

As expected, children have the highest values of speed quotient compared to women and men, indicating that the opening phase of the vocal fold is longer than the closing phase. Analysis of high-speed imaging using phonovibrogram analysis of the opening and closing phases has demonstrated that typically children have a faster closing phase compared to adults (Döllinger et al., 2012). The increased speed quotient from the current study is consistent with the finding of a rapid closure in typically developing children (Döllinger et al., 2012) and is also supported by our previous findings of larger speed index and asymmetry quotient in children (Patel et al., 2014b).

Investigations from high-speed films report that the speed quotient varies directly with intensity levels but not with pitch (Sonesson, 1960; Timcke et al., 1959). The current investigation was performed on participants' self-selected habitual loudness and pitch. Children overall were on the higher end of loudness compared to women and men. However, the loudness levels were within one standard deviation of each other, hence it is safe to state that the loudness did not vary significantly across the groups. This finding, along with the stringent alpha levels, strongly suggests that the differences across the groups are real. However, further investigations need to be conducted to evaluate the influence of loudness levels (soft, mid, and loud) on the speed quotient across children and adults.

While the results indicate that the speed quotient had a significant effect among the populations, it had a smaller

effect size compared to the closing-phase features. Since the speed quotient combines both the opening- and closing-phase intervals in its computation, the higher population variance of the opening phase resulted in a reduced effect size. The mean of the combined normalized average opening and closing velocities is approximately equal to the effect size of the speed quotient. The reduced effect size of the speed quotient, along with that of the opening phase, demonstrates that the closing-phase-based features are more consistent over the populations and indicates that the strong differences in the speed quotient between these populations are driven by the closing phase.

Vibratory motion in children is characterized by large normalized peak displacement compared to adults. The lack of statistical significance in normalized peak displacement between children (0.14 ± 0.04) and men (0.12 ± 0.05) suggests that children have normalized peak displacements that are comparable to those of men. The normalized peak displacement in children is 14% of the length of the vocal fold, whereas in men it is 12%, and in women it is 0.08%. Greater normalized peak displacement in children indicates that the amplitude-to-length ratio is disproportionately larger in children compared to adults. Our findings provide preliminary insights into how children are able to produce sounds as loud as adults with small vocal folds. The disproportionately large amplitude-to-length ratio and relatively shorter closing phase intervals also provide evidence for why children have a hard time making pitch and loudness variations independently of each other (Titze, 1994b). This finding of increased normalized peak geometric displacement is in part supported by our previous study, where in vivo measurement of vibratory amplitude using calibrated laser patterns revealed comparable amplitude-to-length ratios in children to those of adults (Patel et al., 2013). The findings from the current study are from a large number of subjects, compared to the five typically developing children and five adults (men = 2, women = 3) in that previous study.

A greater peak displacement is consistent with an underdeveloped vocal ligament in children, resulting in vocal folds that are more floppy (Boseley & Hartnick, 2006; Hartnick et al., 2005; Sato et al., 2001). Additionally, subglottal pressure in children has been reported to be 2 to 4 times higher compared to adults, which may also influence the measure of normalized peak displacement. The microstructure of the lamina propria is floppy and the vocal-fold ligament less developed (Eckel et al., 1999; Hirano, 1974), suggesting that children have floppier/more elastic vocal folds compared to adults. It appears reasonable to hypothesize that the floppy mucosal layer would respond more rapidly to changes in glottal flow than a mature adult ligament, which because of increased stiffness would exhibit less movement from the applied forces. With greater normalized peak displacement and larger opening-phase velocities, one could hypothesize that a larger percentage of mass is being displaced per cycle, reducing the elastic linearity of the vibrating vocal fold (Chang et al., 2013). Further studies using biomechanical models are necessary to

establish the relationship of peak displacement with the percentage mass being displaced across pitch and loudness conditions.

Methodological Considerations

This study required subjects to phonate at normal loudness level, defined as a subject-determined comfortable level that is close to their habitual conversational pitch and loudness. Further empirical investigations need to be conducted to determine how pitch and loudness modulations affect intra- and intersubject performance across the proposed kinematic measures. In this study, vibratory dynamics were only investigated for the midmembranous portion of the vocal folds. Future studies are needed to simultaneously investigate the vibratory dynamics of the anterior, posterior, and midmembranous portions of the vocal folds. An a priori hypothesis regarding gender was not investigated in this study, due to reduced statistical power from the limited number of participants. The lack of statistical significance for a difference between boys and girls provides validation for combining the children in one group for this study. Further investigations are needed in terms of the developmental profile of growth across girls and boys for understanding the prepubertal development of vibratory motion.

The proposed features do not reflect actual velocity in meters per second or acceleration in meters per second squared but rather a relative distribution of energy over the phonation cycle. These features quantify the qualitative properties observed in clinical images, similar to the features reported by Lohscheller and Eysholdt (2008), who used a glottal-area waveform. The glottal-area waveforms capture the deformation of the entire fold in a summative manner, whereas the features presented here directly relate to the motion of the vocal fold at the glottal midpoint. An advantage of extracting the displacement waveform from specific locations is that it relates directly to the trajectory of a fold edge and allows for the application of signal processing operations (Unnikrishnan et al., 2012) to reduce the impact of rounding off to the nearest pixel and time sample for estimating the features. In children, higher frequencies and smaller displacements in the image plane can result in higher quantization errors relative to adults, which in turn could adversely influence the feature estimates. For example, consider a child with a pitch of 300 Hz filmed at 4,000 frames/s. The sampling interval for a child with a pitch of 300 Hz is 7.5% of the glottal cycle, as opposed to 3% for an adult with a pitch of 120 Hz. The variability of the rounding errors resulting from different sampling intervals, if unaccounted for, may add to the population differences. A similar quantization for the amplitude displacements (pixelation) also occurs, where smaller fold-edge displacements cover fewer pixels during vocal-fold motion.

While many of the feature differences between the populations were driven by normalized displacements, the derivatives allowed for more detail in describing the motions

and energy distributions of the glottal cycle. A potential problem with differentiation, however, is its tendency to amplify high-frequency content, which is often dominated by noise. As discussed earlier, the denoising operation effectively smoothed the displacement waveform by removing the spectral components associated with the independent and random variations due to quantization and other noises, while maintaining the components associated with the quasiharmonic motion of the fold edges. This smoothing was essential for the stability of features derived from the first- and second-order derivatives. Without denoising, the extrapolated waveforms at opening and closing for several cycles would often result in the right and left fold trajectories not meeting within acceptable limits (i.e., between the open fold sample and adjacent closed fold sample). The continuous derivative constraint in the interpolations and extrapolations (cubic spline and linear) also contributed to the stability of the derivative operations. Future studies comparing the normalized kinematic features with the actual velocities and accelerations are needed to provide the relationship between the proposed features and velocity measures in actual units. However, the analysis in this article suggests that these features may not correlate linearly with the true values, due to the nonlinear relationship between glottal length and habitual pitch for maturing vocal folds. Furthermore, the results show that the distinguishing factors of pediatric vocal-fold vibration include larger normalized displacement and greater nonuniformity in the energy distribution over the glottal cycle, with larger relative energy occurring in the closing phase.

Clinical Implications

While the analysis performed here does not provide direct information for assessing force and stress on the vocal folds, the normalized displacement and normalized velocity- and acceleration-based parameters provide information from which inferences regarding collision stress could be made on the basis of how efficiently the vocal fold distributes energy over the phonation cycle. The features based on phases of the glottal cycle (opening and closing) captured significant differences between typically developing prepubertal children and adults. The study findings provide preliminary support for the further investigation of the normalized kinematic features for in vivo characterizations of vibratory behavior in children and adults. The features proposed in this article could complement qualitative observations for comparison with normal or baseline measurements. The findings from this study could provide a framework in which maturation of vocal-fold vibrations for children with and without voice disorders could be studied. The differences in development of vocal-fold motion observed in this study may lead to a clinical framework for early identification of voice disorders in children. With further investigations, an improved understanding of the developmental kinematic features related to vocal-fold motion has the potential to improve early identification, assessment, and management of voice disorders in children.

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