University of Alberta

A Descriptive Study of Pitch Change Mechanisms in Professional Singers

by

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ABSTRACT

The physiology of pitch change encompasses laryngeal, respiratory and supralaryngeal systems. Studies exist to describe these systems during pitch change; however none have looked at these systems simultaneously in professional voice users.

This study examined vocal fold length changes, respiratory kinematics, and suprahyoid muscle activation during one-octave ascending and descending scales in nine female professional singers. Two vocal fold length patterns (*static* and *dynamic*) were observed with pitch change and were significantly correlated with the number of years of vocal training. All participants exhibited similar use of vital capacity across scale production. Surface EMG data were inconclusive as a physiological tremor was induced by the experimental positioning of the participants. The data from my study indicated that the type of vocal fold contraction exhibited by singers may be related to the number of years of training possessed, and that trained singers demonstrate similar patterns of respiratory behaviour.

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INTRODUCTION

The physiology of vocal pitch change involves a complex interplay of the respiratory, laryngeal, and supralaryngeal structures of the speech mechanism. To understand pitch control, studies have focused on the larynx itself through visualization of the vocal folds and perceptual judgements of tension, and on extralaryngeal structures through radiographic observations and three-dimensional imaging.

It has been established that one mechanism of pitch change is related to vocal fold elongation. Findings suggest that the vocal folds elongate as pitch increases, that this relationship is nonlinear, and that this behaviour is variable between vocal task requirements and between subjects[1-6]. For example, when comparing vocal fold length between tasks of speaking and singing, more uniform patterns of elongation are apparent in the singing voice, whereas more variation has been found in the speaking voice[3]. Further, measures of vocal fold length have shown variations between untrained and trained voice users, indicating that the underlying physiological adjustments for pitch change may be different between these two populations. A greater degree of vocal fold length change was observed in non-singers than in singers[4], and smaller increases in length were noted with rising pitch in singers[5]. At higher pitches in singers, a decrease in length was observed, suggesting that change in vocal fold length is pitch range dependent, and that alternative mechanisms for pitch control come into play at higher pitches in passaggio, or "head voice", range[5].

Vocal fold tension also has been identified as a mechanism in pitch control[7-8]. Tension in this case refers to increased stiffness of the vocal folds due to contractile forces within the thyroarytenoid muscles[8], where the muscle tension varies without change in vocal fold length. Perceptual ratings of videolaryngostroboscopic images by experienced judges have shown that vocal folds were rated thinner, narrower and more tense with increasing frequency[9]. In a study of a glissando in an untrained male singer, vocal fold length was the most stable laryngeal parameter, indicating that it was not the primary contributor to pitch change; rather, vocal fold tension was thought to be the primary contributor to pitch change in the context of unchanging vocal fold length[10].

Pitch is not controlled solely within the larynx itself, rather various extralaryngeal factors, such as vertical movement of the larynx and respiratory support, have the potential to contribute to pitch change. Elevation of the larynx in conjunction with pitch increase and depression of the larynx in conjunction with pitch decrease have been widely documented in professional singers and singing students[11-14]. The superior-inferior laryngeal excursions associated with pitch change appear to be smaller in professional singers than in singing students[12]. Forward horizontal movement of the hyoid bone in higher frequencies also has been observed, likely facilitating rotation of the thyroid cartilage for raising pitch[14]. Supraglottal widening of the vocal tract at the level of the pyriform sinuses in falsetto singing also has been observed during three-dimensional imaging of the vocal apparatus and supralaryngeal structures[15].

Lung volume has been found to have an effect on vertical larynx position in untrained subjects, with high lung volume associated with a lower larynx position[13]. In professional singers, investigation into respiratory adjustments during singing has demonstrated that breath groups are typically initiated at high lung volumes, with a wide range of vital capacity used[16]. It also has been found that quick shifts in volume from the abdomen to the rib cage are common during transitions between inspiration and expiration, which may be a means of controlling high pressure against laryngeal tension at high lung volumes[16-17]. Therefore, both supralaryngeal and respiratory mechanisms need to be considered in conjunction with laryngeal adjustments in pitch control.

In addition to the various physiological mechanisms involved with pitch control, the type of voice user must be considered. Differences in vocal training and vocal use may influence the manner in which laryngeal and supralaryngeal mechanisms are used for pitch control. Evidence from acoustic measures has shown that significant differences exist between trained and untrained voice users. For example, in a study of prolonged voice use, an untrained voice user reported experiencing fatigue more quickly while displaying no significant changes in jitter and shimmer, while a trained singer tended to adapt well, showing significant changes in shimmer values that recovered to prefatigue levels during rest[18]. In another study, acoustic measures of intensity, jitter ratio, shimmer, and signal-to-noise ratio were negatively affected in untrained singers before and after prolonged loud reading tasks, while trained singers exhibited more consistent patterns in acoustic measures[19]. Muscle tension patterns defined by laryngeal appearance during phonation, including an open glottic chink, medial compression of the false vocal folds, partial anteroposterior contraction of the larynx, and extreme anteroposterior contraction where the arytenoids contact the petiole of the epiglottis, are more frequently observed in untrained singers than trained singers[20]. Trained singers also exhibit more variability in respiratory behaviour[17,21] and their respiratory behaviour differs significantly from respiratory norms derived from untrained voice users[22].

Previously discussed evidence supports the idea that both length and tension are necessary for pitch control, which may be manifested by the use of two types of muscle contractions: isotonic, involving change in length, and isometric, involving increase in tension without change in length. Preliminary data[23] suggest that specific types of adjustments may contribute to vocal fatigue in untrained voice users. Specifically, subjects experiencing vocal fatigue exhibited less vocal fold length change, which is associated with isometric contractions, while subjects who did not experience vocal fatigue exhibited more length change, which is associated with isotonic contractions[23]. Whereas evidence suggests that trained voice users make different physiological adjustments than untrained voice users, little is known about physiological variability within vocal athletes. Moreover, it is not clear whether isometric versus isotonic contractions are salient physiological features for the prediction of vocal performance, endurance, or health of the professional voice user. Understanding the physiology of pitch change in professional voice users has tremendous implications for the treatment of this population, who rely on their voices to contribute to society through their professions.

The present study examined laryngeal, respiratory and supralaryngeal behaviour during tasks that required pitch modifications in professional singers. The measures of vocal fold length change were adapted from McCue[23]. In addition to measures of vocal fold length change, respiratory kinematic data were collected in the present study to determine how respiratory behaviour may be related to different types of vocal fold configurations. Also, surface EMG was used to assess muscle activity above the larynx to document extrinsic suprahyoid muscle adjustments made during pitch changes.

METHODS

Participants

Participants included female singers between the ages of 18 and 40 years old, with at least 4 years of formal voice training, and singing for at least 20 hours per week at the time of recruitment and testing. Participants were recruited from post-secondary educational institutions and through the support of classical and musical theatre singing instructors and professors in the Edmonton area. Participants were excluded if they exhibited signs or history of any of the following characteristics: less than 4 years of continuous voice training; outside the age range of 18-40 years old; less than 20 hours per week of voice use for singing; abnormal appearance or function of the larynx upon visualization with rigid laryngeal endoscopy; abnormal acoustic voice properties when compared with norms reported in Colton & Casper[24]; laryngeal surgery or trauma to the larynx; voice, neurogenic, psychogenic, or swallowing disorders; gastro-esophageal reflux disease; hormone imbalance or disorder; menopause or hormone therapy; previous voice therapy; smoking within the last 5 years; consumption of alcohol within 48 hours of the study; consumption of caffeine within 24 hours of the study; less than 64 oz of water per 24 hours for 48 hours before study; inability to tolerate rigid laryngeal endoscopy or perform tasks during endoscopy; severe anterior-posterior or medial squeezes in larynx that obscure the view of the vocal folds; use of prescription medications known to cause changes in laryngeal structures, function, mucosa, or muscle activity (list provided by National Centre for Voice and Speech (NCVS) at http://www.ncvs.org/ncvs/info/vocol/rx.html, accessed March 2, 2006); presence of symptoms of cold or flu in past 48 hours; and, perceptual judgement of "dysphonic" during phone interview screening.

Thirteen participants volunteered for the study; four of whom did not meet inclusion criteria. The remaining 9 female professional singers from the ages of 19 to 35 years old were included in this study. Participant characteristics and details reported in the Vocal Questionnaire[23] (Appendix A) are shown in Table 1.

Table 1. Participant Characteristics and Details from Vocal Questionnaire

	Age	**Reason for exclusion**	**Type and level of training**	**Occupation**	**Types of singing**
E1	25		in BMus program, 16 years of training	voice instructor & student	choral, classical, solo
E2	27	bilateral nodules on vocal folds; referred to voice clinic	MMus, 10 years of training	music instructor, choir director, piano & voice teacher	choral, solo, pop/rock/jazz
E3	19	irregularity & edema along edges of vocal folds at multiple sites; referred to voice clinic	in Theatre Arts diploma program, 4 years of training	student	choral, solo, musical theatre

E4	26		BMus, 10 years of training	music retail, theory/voice teacher	classical, musical theatre, solo, opera, pop/rock/jazz
E5	20		in Theatre Arts diploma program, 7 years of training	student	musical theatre, solo
E6	30		in PhD program, 12 years of training	sessional voice instructor, doctoral candidate	choral, classical, solo
E7	26	images of vocal folds could not be obtained	in BMus program, 13 years of training	student, retail position	choral, solo, opera
E8	20		in a BMus program, 9 years of training	student	choral, classical, solo, opera
E9	20		in Theatre Arts diploma program, 5 years of training	student	classical, musical theatre, opera, pop/rock/jazz
E10	20		in Theatre Arts diploma program, 7 years of training	student	choral, classical, musical theatre, solo
E11	19	insufficient number of vocal fold images obtained	in Theatre Arts diploma program, 12 years of training	actor/singer	solo, classical, opera, musical theatre
E12	35		BMus, 15 years of training	teacher, office assistant, musician	choral, classical, solo
E13	35		MMus, 16 years of training	musician, teacher, singer	choral, classical, solo

Instrumentation

Several types of instrumentation were connected to a Kay Digital Swallowing Workstation (V 3.0.1, Lincoln Park, NJ) as shown in Figure 1. To capture digital video of vocal fold movement, a 90-degree rigid endoscope (Kay, model 9106) was used with a Toshiba camera (Model 3CCD) and a Kay Xenon lightsource (Model 7150) in conjunction with a lapel microphone to record vocalizations. To capture kinematic respiratory behaviour, a variable inductance plethysmograph (Respitrace, Ambulatory Monitoring Systems, New York) was used and calibrated for vital capacity and tidal breathing using a hand-held respirometer (Ferraris, Orchard Park, NY) and a four channel digital storage oscilloscope (Tektronix TDS 2014). The sum contribution of ribcage and abdomen signals was captured to the Kay Swallowing Signals Lab (Model 7120, Lincoln Park, NJ) at a sampling rate of 250 Hz/second, and resulted in an output signal in volts. Disposable surface EMG electrodes (Tyco Uni-Patch, Disk 7500, Wabasha, MN) with skin-compatible adhesive on the back of the array were placed under the participant's mandible with electrode gel to measure the response of the most external suprahyoid muscles, the anterior belly of the digastric and mylohyoid muscles. The signals were captured to the Kay Swallowing Signals Lab with electrodes arranged within a soft pad in a three-clip assembly consisting of two active leads and one ground lead. Video, audio, respiratory and EMG signals were time-locked in capture.

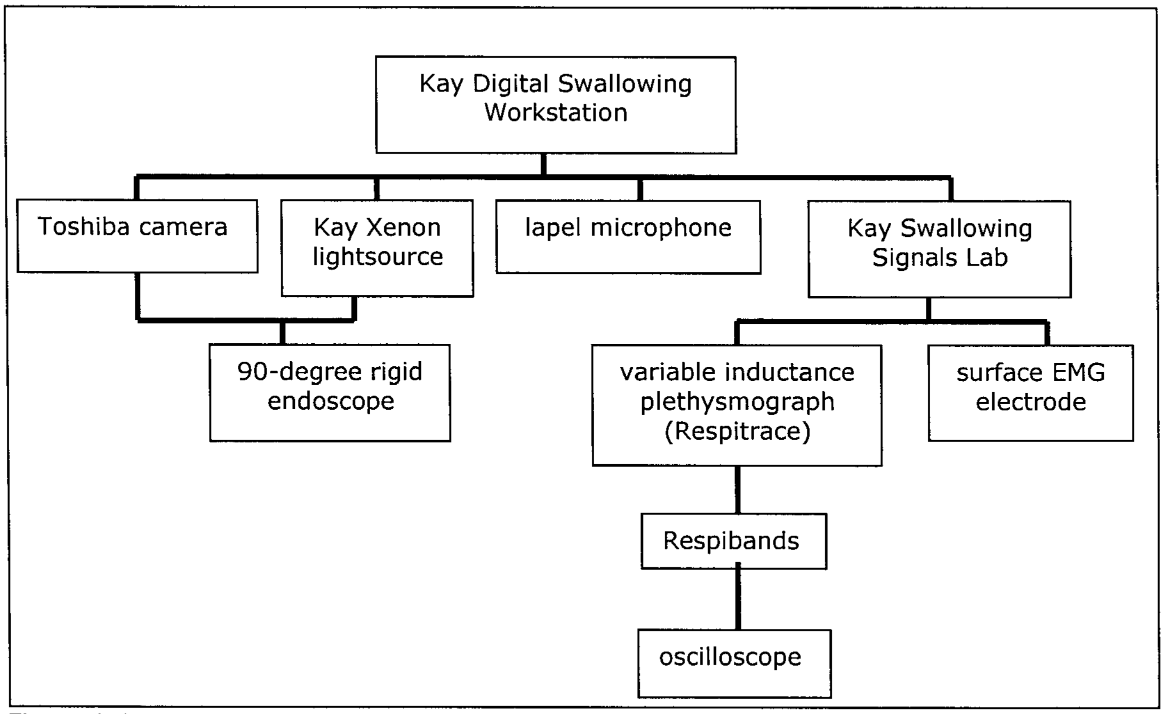


Figure 1. Instrumentation.

Procedures

Telephone Screening. Potential participants for the study underwent a brief interview screening over the telephone (adapted from McCue[23], Appendix B). Questions about age, current prescription medication use, and level of vocal training were asked. None of the participants indicated use of prescription medications that were reported to cause changes in laryngeal structures, function, and/or mucosa by the NCVS during the screening. "Yes" or "no" questions regarding respondents' history of laryngeal surgery, traumatic injury to the larynx, voice disorder, emotional/physical disease requiring treatment, menopause, voice therapy, and smoking also were asked. None of the participants responded "yes" to any of these questions; therefore, all potential participants were invited to take part in a vocal screening session.

Laboratory Screening Session. An in-person screening session took place in the Head and Neck Surgery Functional Assessment Laboratory at the Craniofacial Osseointegration and Maxillofacial Prosthetic Rehabilitation Unit (COMPRU). Participants completed the Vocal Questionnaire (Appendix A), as well as the Voice Handicap Index[25] (Appendix C). The Voice Handicap Index consists of three subscales, Functional (F), Physical (P), and Emotional (E), as well as a total score, all of which are intended to determine if any psychosocial handicapping effects related to the voice were self-perceived. A higher score on any subscale indicates a greater self-perceived severity. None of the participants indicated a self-perceived voice handicap according to their total scores and so were encouraged to continue with laryngeal screening of the vocal folds via endoscopy.

Preliminary screening using rigid laryngeal endoscopy also was done to assess the appearance and function of the vocal folds. Any participants who exhibited abnormal properties, such as the presence of nodules or polyps or abnormal closure patterns, were excluded from the study (see Table 1). Participants who were excluded from the study were given an explanation of the exclusionary criteria and were referred to a specialist team at the Voice Clinic at the Glenrose Rehabilitation Hospital for further assessment or treatment if appropriate. Participants who did not exhibit any exclusion criteria were invited to continue with the remainder of the experimental lab session.

Experimental Laboratory Session: Acoustic Analysis. Acoustic data were obtained for each participant using the KayPentax Computerized Speech Lab (Model 4400, Version 2.7, Lincoln Park, NJ). A Shure 512 unidirectional head mounted microphone was used, with the microphone placed 4cm away from the participant's mouth. Participants were provided with instructions and models for vocal and speech tasks by the researcher. Audio recordings were saved onto the computer's hard drive at a sampling rate of 44 KHz. Acoustic measures included: average fundamental frequency of sustained ten-second /a/ (**F_0/a/**) over two trials, and average fundamental frequency of ten seconds of spontaneous speech (**F_0speech**) over two trials. Additional tasks recorded and later measured for duration included: maximum phonation time (**MPT**) of sustained /a/ over three trials, and s/z ratio (**s/z**) over two trials. A perceptual judgement about voice quality was made by the researcher and each participant's voice was categorized as "breathy", "rough", "tense" or "normal". (See Appendix D for data collection form)

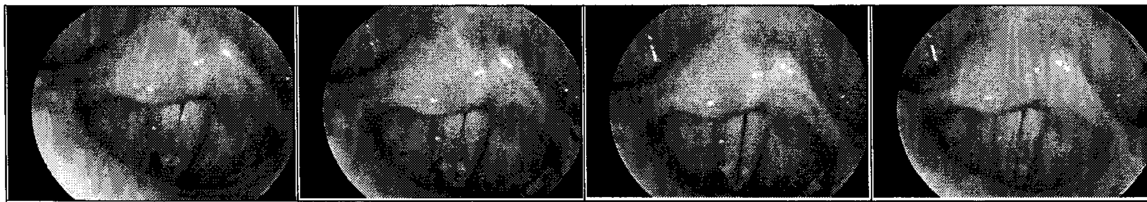
Experimental Laboratory Session: Respitrace Procedure. Two Respitrace bands were placed around the participant's chest wall. One band was positioned around the rib cage and one around the abdomen. Rib cage and abdominal movements were then calibrated through observation of rib cage and abdomen kinematic tracings on an oscilloscope (Figure 1) during a series of isovolume maneuvers. Appropriate gain adjustments were applied to both chest wall signals as prescribed by Hixon et al[26]. These adjustments served to establish the relationship between the relative motion of the rib cage and abdomen in order to derive motion representing lung volume.

In order to obtain known lung volume values that would then be used to correspond to voltage changes in the signal, two tasks were performed by each participant. First, three to four trials of tidal breaths were performed, with the expiratory volume determined by using a hand-held respirometer. Second, three trials of vital capacity maneuvers were completed, again using the respirometer to measure volume expired. All respiratory measurements were time-locked to the kinematic signals derived from the Respitrace.

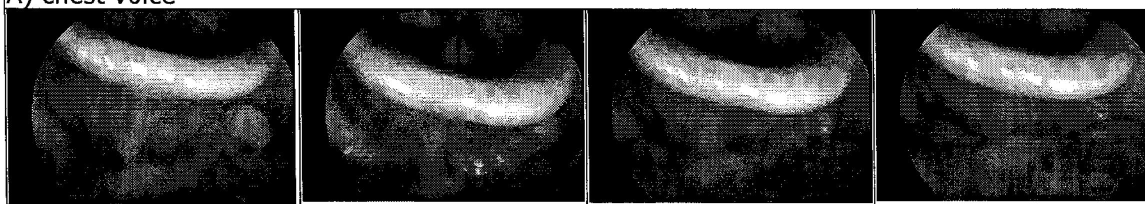
Experimental Laboratory Session: Surface Electromyography. Surface EMG electrodes were placed under the mandible to measure the response of the most external suprahyoid muscles, those being the anterior belly of the digastric and mylohyoid muscles. Placement of electrodes was determined by the size and shape of the neck and signal sensitivity. Surface EMG signals were captured to the Kay Swallowing Signals Lab (Figure 1), which sampled the signal at 250 cycles per second and recorded it in real time. This allowed for time-locked capture of the surface EMG signals along with endoscopic and respiratory signals.

Experimental Laboratory Session: Endoscopic Examination. Participants were given instructions regarding production of the ascending and descending major scales that were recorded during endoscopy. The majority of participants performed the tasks leaning forward, elbows on knees, and chin jutted anteriorly and upwards. This allowed for superior visualization of the vocal folds, as it was otherwise often difficult to obtain images of them, especially of the anterior commissure. The participants were instructed to pull their tongue out and down while holding it with gauze in order to get an unobstructed view of the vocal folds with the scope. All participants also were instructed to attempt to produce scales on the vowel /i/, as this aided in getting a better view of the vocal folds.

Participants were asked to sing one-octave scales beginning at a comfortable pitch, preferably in their "chest voice" or the lower register of their voice. This pitch range was chosen as previous examinations determined that the supralaryngeal structures obscured the vocal folds when the singers produced scales in their "head voice". See Figure 2 for a comparison of images obtained between chest voice and head voice in one experimental participant. Participants were asked to sing the ascending scale and descending scale in succession, taking as many trials as needed to obtain images of at least two full ascending and two full descending scales.



A) chest voice



B) head voice

Figure 2. Comparison of top 4 notes in ascending scales produced by one professional singer, in chest voice (A) and head voice (B).

Analysis Protocol

Analysis of Acoustic Data. F_0/a/ and F_0speech were analyzed in CSL through the Multi-Dimensional Voice Program by running a MDVP analysis, obtaining a mean F_0 value for each sample. Times for MPT and /s/ and /z/ productions were recorded, and s/z ratios calculated.

Analysis of Respiratory Kinematic Data. Specific points in time that corresponded with each note sung by a participant were tagged using the tagging function within the Kay Pentax Swallowing Workstation software. In addition, tags were created at the following points in the kinematic data: the beginning of inspiration for each scale, the beginning of expiration for each scale, and the end of expiration for each scale. The points during the respiratory calibration corresponding to the beginning and end of expiration for the three tidal breaths and three vital capacity trials also were tagged. A list of tags was produced for each participant, with information about the voltage and exact time of the tag. The respiratory data were then exported as a .txt file, and imported into PowerLab (16sp, ADInstruments) for analysis.

After the .txt file was imported into PowerLab, two transformations were performed on the voltage signal using the known lung volumes obtained by the hand-held respirometer in the tidal breath and vital capacity tasks. First, a transformation was done to convert volts into litres and zero the waveform to End Expiratory Level (EEL). This was done by using the following formula:

$$L = L_1 + (L_2 - L_1)/(V_2 - V_1) * (V - V_1)$$

where L = the transformed signal,

L_1 = the known lung volume from a tidal breath (L),

L_2 = 0 (the bottom of the tidal breath or EEL) (L),

V = the voltage signal,

V_1 = top of the tidal breath (beginning of expiration) (V),

V_2 = bottom of the tidal breath (end of expiration) (V).

Second, a transformation was performed in order to obtain a signal that represented percent vital capacity (%VC) using the following formula:

$$\%VC = [100*(L - minVC)]/VC$$

where L = the lung volume signal,

$minVC$ = minimum lung volume corresponding to the end of expiration during the vital capacity task (L),

VC = the vital capacity (L).

These two transformed waveforms were then used to obtain lung volume and percent vital capacity values at the following points for each scale: beginning of inspiration, beginning of expiration, end of expiration, and each pitch in the scale. The values were taken for each full scale sung by each participant from whom images were also measured.

Analysis of Surface Electromyographical Data. As with the respiratory data, the EMG waveform was time-locked with both the video and respiration. The raw EMG data were then exported as a .txt file. For each participant, one sample each of continuous singing and rest before singing were taken for analysis. The longest sample of continuous singing was used. The rest sample was taken during the time that the participant had her tongue pulled out just prior to producing the scale. All samples were at least 13 seconds in length at a sampling rate of 250 Hz (due to the limitation of the hardware for acquiring multiple, time-locked signals). The rest and singing EMG samples were zero averaged. The following values were obtained from the zeroed sample: standard deviation of amplitude, minimum amplitude, maximum amplitude, and range of amplitude. The .txt file samples were then imported into MatLab (version 7.1), where cross-correlations were performed to obtain EMG frequencies data.

Analysis of Endoscopic Images. For each participant, a still image of the vocal folds was obtained from the digital video recording for each note in each scale produced. A vertical to horizontal ratio was used to determine change in vocal fold length across pitch changes. The vertical length was taken along the medial edge of the right vocal fold, from the anterior to posterior commissures. Only images where the anterior commissure was visible were used in the analysis. The horizontal length was taken from a landmark point to the space between the vocal folds. The landmark point used for the horizontal length was picked specifically for each participant, depending on what structures were constantly visible, by the researcher and co-supervisors. The landmark point was chosen to be a point that was stable and unchanging and was used across all images of one participant. The epiglottis has been used as a landmark for measurement in previous studies of untrained voice users[23] and pilot work for this study (Appendix E), but it was not used in the present study after it became apparent that the epiglottis was not a constant structure across each image that was obtained. A 90 degree angle between the vertical and horizontal lengths was used to ensure stability of measurement over images. When performing measurements, the vertical length was completed first, and then the horizontal length was completed at a 90 degree angle from the vertical length.

Figure 3 displays a sample image from one participant. If the horizontal landmark was not close in proximity to the vocal folds, a line was drawn from the space between the vocal folds to act as a reference. For sample images from each of the participants, refer to Appendix F.

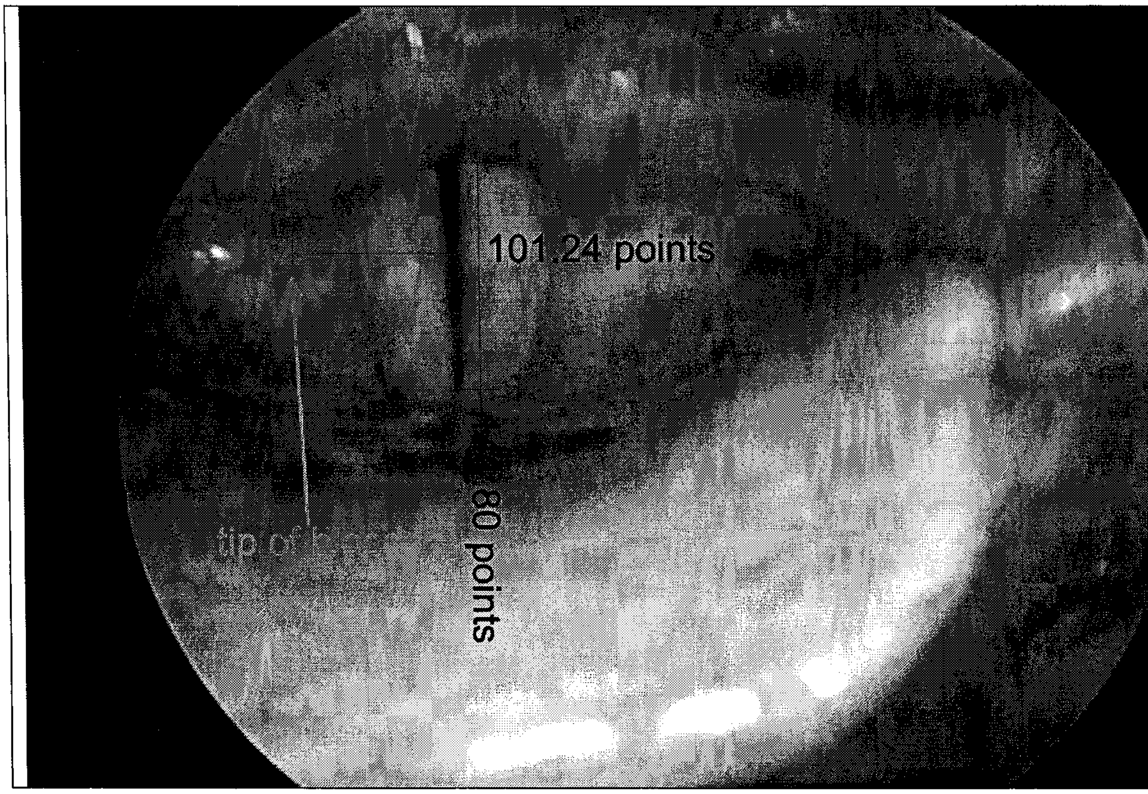


Figure 3. Sample measurement image from one participant (E12). The vertical length was taken from the posterior to anterior commissures along the right vocal fold. The green arrow indicates the specific landmark used for the horizontal measurement. The horizontal measurement was taken at a 90-degree angle from the vertical measurement, from the tip of the blood vessel to the space in between the vocal folds.

Three trials of measurements were taken for each analyzed image to establish intra-rater reliability. A ratio was calculated from the vertical measurement over the horizontal measurement for each of the measurement trials, and a mean ratio was obtained. All measurements were performed by the researcher, and all images from a randomly selected participant, approximately 10% of all analyzed images, also were measured by a research assistant to obtain inter-rater reliability. Reliability analyses indicated the correlation for intra-rater reliability was $r = 1.00$, and for inter-rater reliability, $r = 0.91$.

RESULTS

Questionnaires. Results from the VHI are shown in Table 2. None of the participants indicated a significant handicap except for E13 who indicated a mild handicap on the Functional subscale.

Table 2. Voice Handicap Index Scores

Participant	Voice Handicap Index			
	F	**P**	**E**	**total**
E1	6	2	0	8
E4	8	4	2	14
E5	0	2	0	2
E6	5	2	0	7
E8	2	4	1	7
E9	0	5	0	5
E10	3	8	1	12
E12	3	5	1	9
E13	9	3	3	15

Acoustic Analysis. The mean F_0/a/ for all participants was 209.54 Hz with a range from 160.97 Hz to 226.63 Hz. The mean F_0speech for all participants was 196.99 Hz with a range from 162.69 Hz to 212.49 Hz. For MPT, the mean was 15.36 s, with values ranging from 11.14 s to 20.90 s, and the mean s/z ratio was 1.16 with a range of 0.93 to 1.49. All participants fell within the expected range for these measures[24]. Voice quality for all participants was judged to be "normal". See Appendix G for detailed data.

Respiratory Kinematic Data. The mean vital capacity for all participants obtained with the respirometer was 3.45L with a range from 2.54L to 4.18L. The range of values of the mean percent vital capacity (%VC) at each note in ascending and descending scales produced by each participant are shown in Table 3. All participants demonstrated similar respiratory patterns, regardless of the vocal fold pattern exhibited, and regardless of whether they took one or two breaths (see Appendix H for figure). In participants who took 2 breaths, it was interesting to note that they consistently started higher in %VC to begin the ascending scale than the descending scale. In terms of range of %VC over the trials of ascending and descending scales produced, participants E4, E6, E8, E9, and E10 displayed large ranges over the scales, indicating that there was more variation in their use of %VC across different trials (see Appendix H for figure). Participants E1, E5, E12 and E13 displayed smaller ranges, indicating that they were more consistent in their use of %VC across different trials.

Table 3. Mean %Vital Capacity Ranges for Scales Produced by Each Participant

	maximum to minimum %VC	%VC Range
E1	63.36 - 35.13	28.23
E4	81.18 - 38.92	42.26
E5	96.66 - 70.35	26.31
E6	60.43 - 33.82	26.61
E8	58.79 - 25.40	33.39
E9	85.40 - 36.48	48.92
E10	78.80 - 45.39	33.41
E12	65.06 - 41.31	23.75
E13	76.52 - 54.15	22.37

EMG Analysis. Results from analysis of EMG amplitudes and frequencies for the conditions of rest and singing were obtained (see Appendix I). Three patterns of behaviour were seen in EMG amplitude ranges: 1) larger amplitudes in rest than singing, 2) larger amplitudes in singing than rest, and 3) similar amplitudes in both rest and singing. By visual comparison, 6 out of 9 participants (E1, E4, E5, E6, E10, E13) demonstrated similar amplitudes in both rest and singing, 1 participant (E8) demonstrated a larger amplitude in singing than rest, and 2 participants (E9, E12) demonstrated larger amplitudes in rest than singing. Results from cross-correlations performed on EMG signal frequencies indicated a difference between rest and singing demonstrated by all singers. Rest cross-correlation frequencies were characterized by peaks occurring at about 10 Hz and looked similar to postural tremor found in outstretched limbs in normal individuals[27]. During singing, cross-correlation frequencies were markedly lower (below 3Hz) suggesting a different muscle activation pattern than during the rest condition. An exemplar of the cross-correlation analysis (E6) for rest and singing is shown in Figure 4 (see Appendix I for cross-correlograms for all participants).

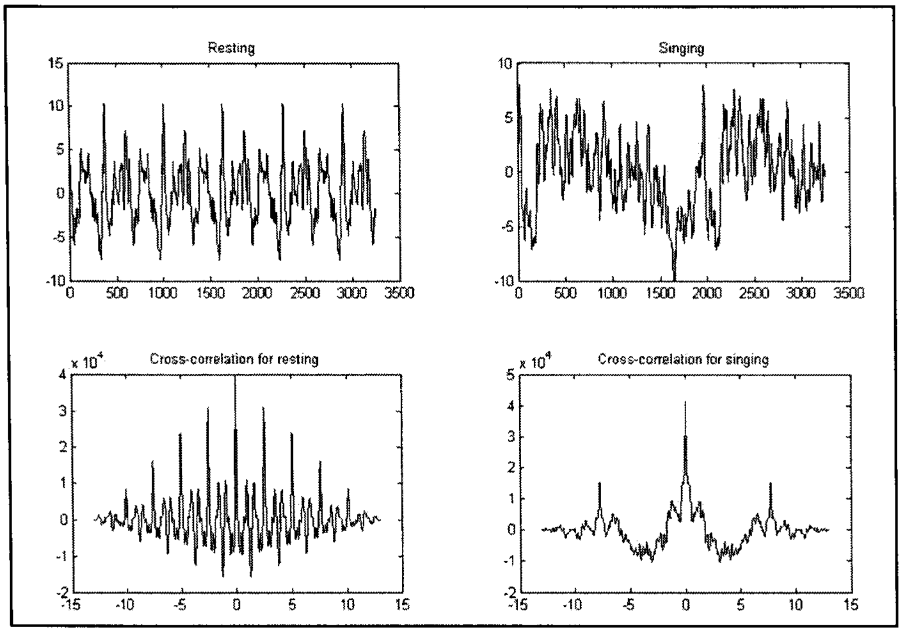


Figure 4. EMG signals and cross-correlograms.

<u>Endoscopic Analysis of the Vocal Folds.</u> Mean ratios of vertical to horizontal vocal fold measurements for ascending and descending scales are displayed in Figures 5a and 5b. These mean ratios were determined by taking the mean of the ratios obtained from all trials of a specific note sung in ascending and descending scales. The resulting mean curve for the ascending and descending scales for each participant was then adjusted to the same starting point to visually normalize the resulting trends. Two patterns of behaviour for pitch change were identified: 1) a static pattern where the vocal fold ratio showed minimal variation with pitch change, and 2) a dynamic pattern where the vocal fold ratio showed great change with increase and decrease in pitch. Figure 5a displays participants showing a static pattern that may be associated with the use of isometric contractions for pitch control, while figure 5b displays those with a dynamic pattern that may be associated with the use of isotonic contractions for pitch control. Because measurable images for each note of each scale could not be obtained for every participant, there are missing data points; however, trends in behaviour are still observable. A F_{max} test[28] also was performed, which indicated a significant difference between the variances of the two groups ($F_{max} = 15.86$, $p < 0.05$). Figure 6 displays the best fit curves for both groups.

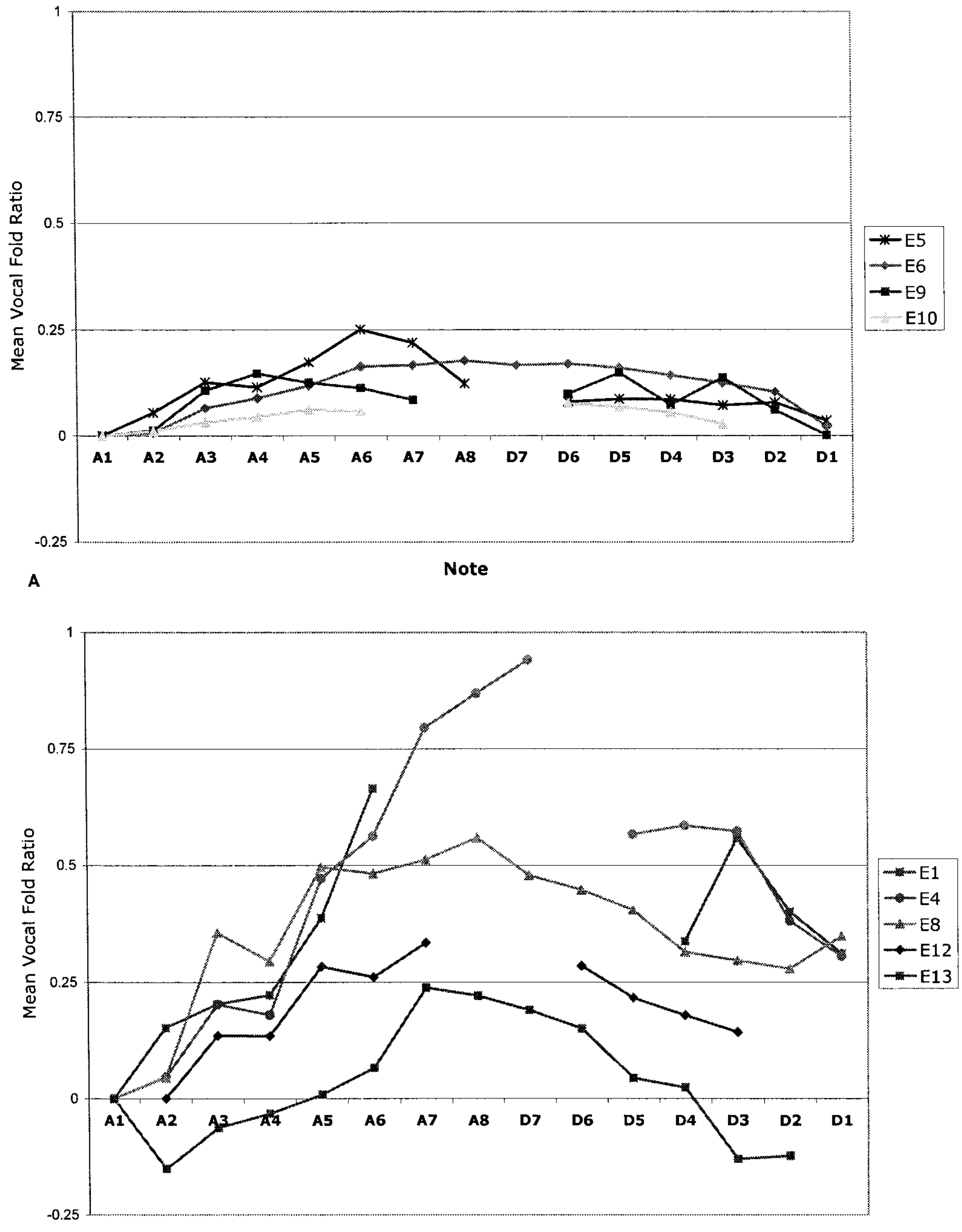


Figure 5. Adjusted mean vocal fold ratios for ascending and descending scales. Participants exhibiting a static pattern (A) and participants exhibiting a dynamic pattern (B) are shown. The mean vocal fold ratio (vertical measurement over horizontal measurement) is displayed on the vertical axis while the horizontal axis displays each note produced in the scales. A1

refers to the lowest note in the ascending scale, A2 to the next lowest note in the ascending scale and so forth up to A8, the highest note in the scale. D7 refers to the next highest note in the descending scale and so forth until D1, the lowest note in the descending scale.

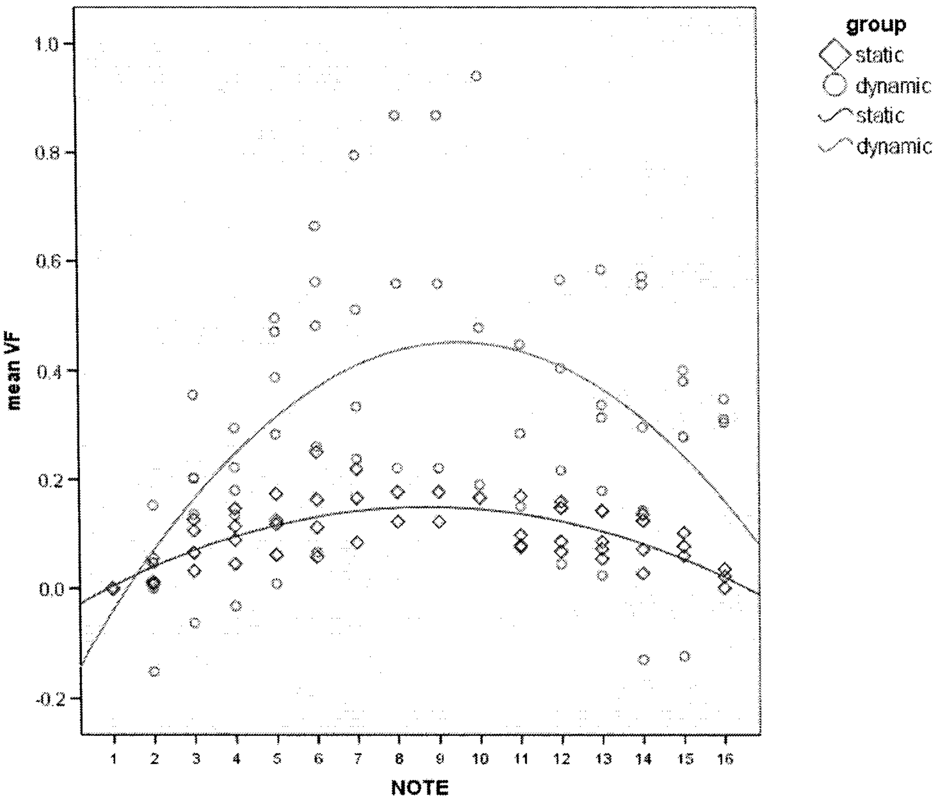


Figure 6. Best fit curves for dynamic and static patterns. Notes 1-8 refer to notes A1-A8 in the ascending scale, while notes 9-16 refer to notes D8-D1 in the descending scale.

As the participants were instructed to start at a note that was comfortable in their "chest voice", the pitch ranges produced varied across participants. Table 4 shows the mode pitch ranges sung by each participant.

Table 4. Mode Pitch Ranges for Scales Produced by Each Participant

	Mode Pitch Range – minimum to maximum Hz (semitone)
E1	185.00 (F#3) - 369.99 (F#4)
E4	233.08 (A#3) - 466.16 (A#4)
E5	196.00 (G3) - 392.00 (G4)
E6	164.81 (E3) - 329.63 (E4)
E8	233.08 (A#3) - 466.16 (A#4)
E9	164.81 (E3) - 329.63 (E4)
E10	196.00 (G3) – 392.00 (G4)
E12	196.00 (G3) - 392.00 (G4)
E13	138.59 (C#3) - 277.18 (C#4)

To determine what factors were influential in separating participants into the two patterns of behaviour represented in Figures 5a and b, between-groups analyses of variables exhibiting skewed data were completed via Mann-Whitney tests, while variables with data that were not skewed were explored via independent samples t-tests. Table 5 shows descriptive statistics for variables that were considered in the analyses. Significant differences were found in the number of years of training between the groups (see Figure 7 for boxplot). The dynamic group possessed more years of training while the static group possessed less (Mann-Whitney, $Z[7] = -1.23$, $p = 0.048$). No significant differences between the two groups were observed for the remaining variables (see Appendix J for additional boxplots), however the comparative boxplots for vital capacity, maximum and minimum %VC during scale production, and the Functional subscale of the VHI proved noteworthy (see Figures 8, 9 and 10). For recorded vital capacities, the dynamic group was characterized by a smaller range that fell within the upper end, while the static group had a larger range that included values from the lowest to the higher values. For both maximum and minimum %VC during scale production, the static group demonstrated a greater range, while the dynamic group had a smaller range. For the VHI, the dynamic group scored higher on the functional (F) subscale. A Pearson correlation revealed that scores on the VHI Functional subscale were positively correlated with the number of years of experience ($r = 0.70$, $p = 0.035$).

Table 5. Descriptive Statistics for Additional Variables

Variable	Group	Mean ± SD	Minimum-Maximum
age (years)	static	22.50 ± 5.00	20 - 30
	dynamic	28.20 ± 6.61	20 - 35
number of years of training	static	7.75 ± 2.99	5 - 12
	dynamic	13.20 ± 3.42	9 - 16
vital capacity (L)	static	3.39 ± 0.69	2.54 - 4.18
	dynamic	3.49 ± 0.57	2.54 - 3.91
maximum phonation time (s)	static	15.69 ± 3.26	11.97 - 19.89
	dynamic	15.09 ± 4.82	11.14 - 20.90
s/z ratio	static	1.27 ± 0.19	1.03 - 1.49
	dynamic	1.07 ± 0.11	0.93 - 1.17
F_0 /a/ (Hz)	static	218.04 ± 5.11	212.17 - 224.64
	dynamic	202.73 ± 25.01	160.97 - 226.63

F_0 speech (Hz)	static	197.33 ± 16.35	180.81 - 212.49
	dynamic	196.73 ± 19.83	162.69 - 210.78
mode low pitch for scale (Hz)	static	180.41 ± 18.01	164.81 - 196.00
	dynamic	197.15 ± 39.24	138.59 - 233.08
mode high pitch for scale (Hz)	static	360.82 ± 39.01	329.63 - 392.00
	dynamic	394.30 ± 78.49	277.18 - 466.16
maximum %VC for scale	static	80.32 ± 15.17	60.43 - 96.66
	dynamic	68.98 ± 9.44	58.79 - 81.18
minimum %VC for scale	static	46.51 ± 16.64	33.82 - 70.35
	dynamic	38.98 ± 10.43	25.40 - 54.15
minimum EMG amplitude at rest	static	-7.86 ± 3.41	-10.62 - -3.16
	dynamic	-7.80 ± 3.47	-12.82 - -3.51
maximum EMG amplitude at rest	static	12.65 ± 8.52	4.17 - 24.45
	dynamic	13.34 ±9.56	5.27 - 29.83
minimum EMG amplitude during singing	static	-7.38 ±2.26	-9.98 - -5.13
	dynamic	-6.70 ± 4.11	-12.48 - -1.92
maximum EMG amplitude during singing	static	8.70 ± 2.75	5.27 - 11.77
	dynamic	10.83 ± 5.17	5.12 - 17.90
VHI-functional	static	2.00 ± 2.45	0 - 5
	dynamic	5.60 ± 3.05	2 - 9
VHI-physical	static	4.25 ± 2.87	2 - 8
	dynamic	3.60 ± 1.14	2 - 5
VHI-emotional	static	0.25 ± 0.50	0 - 1
	dynamic	1.40 ± 1.14	0 - 3
VHI-total	static	6.50 ± 4.20	2- 12
	dynamic	10.60 ± 3.65	7 - 15

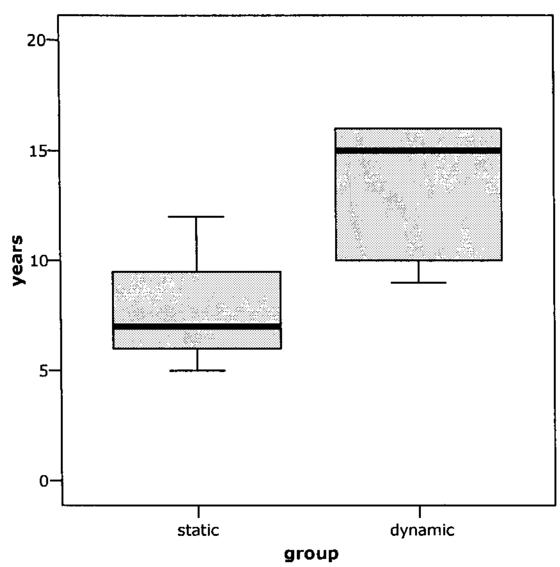


Figure 7. Boxplot comparing number of years of training for static and dynamic groups.

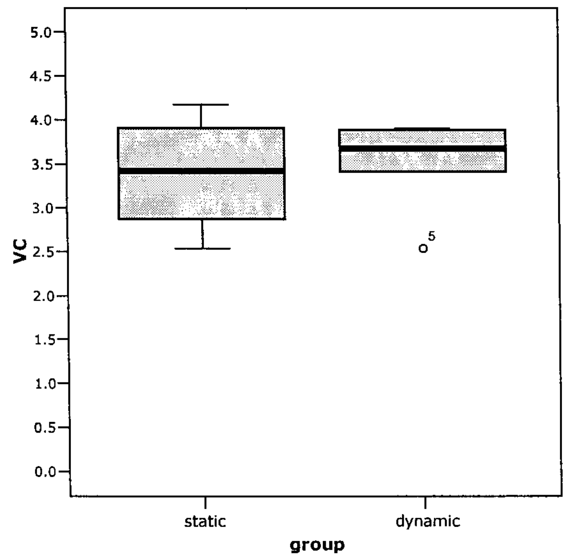


Figure 8. Boxplot comparing vital capacity for static and dynamic groups.

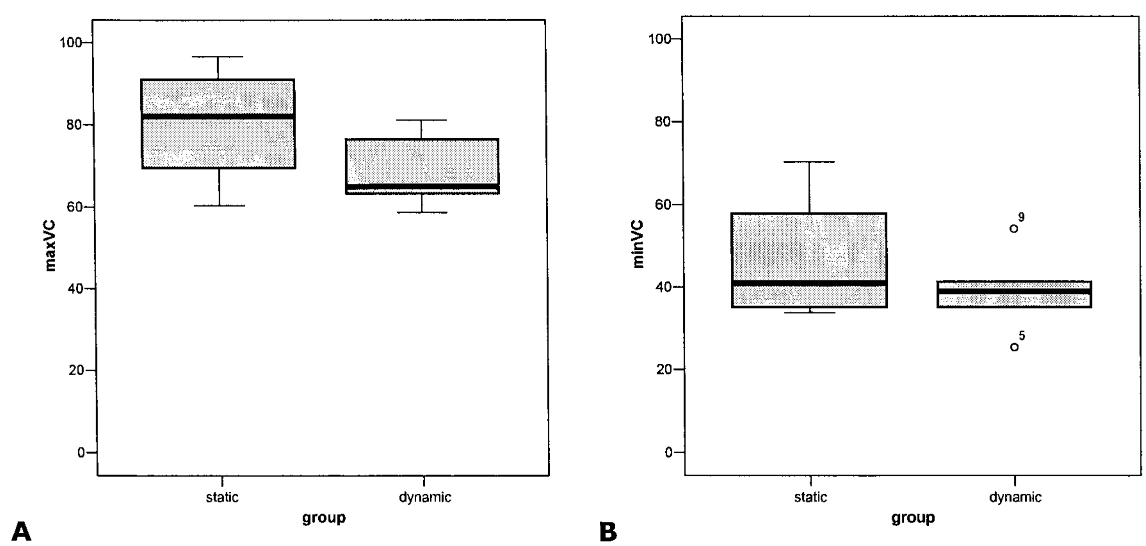


Figure 9. Boxplots comparing maximum (A) and minimum (B) %VC in production of scales for static and dynamic groups.

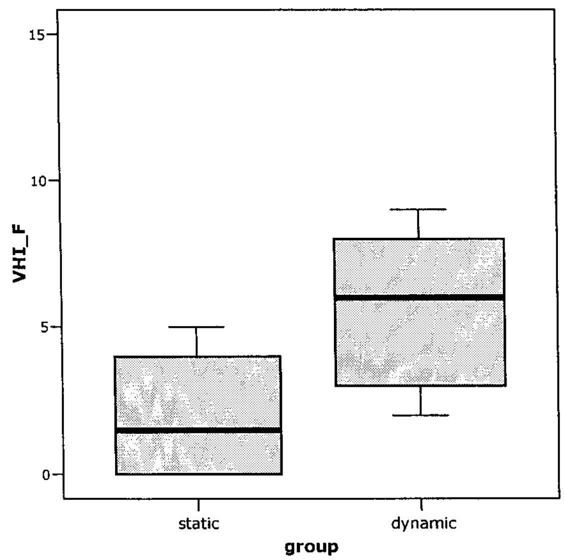


Figure 10. Boxplot comparing the Functional subscale of the VHI for static and dynamic groups.

A Pearson correlation was run to determine whether any other correlations existed between the variables. F_0 for speech was positively correlated with the participants' mode starting and ending pitches for the scales ($r = 0.79$, $p = 0.012$). Number of years of training was positively correlated with age ($r = 0.83$, $p = 0.006$). Minimum and maximum %VC used in the scales were positively correlated with vital capacity (maximum %VC: $r = 0.72$, $p = 0.028$ and minimum %VC: $r = 0.69$, $p = 0.039$).

Other categorical variables that were considered included: voice quality, type of training, and responses on the Vocal Questionnaire regarding occupation, types of singing, singing use, vocal fatigue, and positive and negative symptoms after moderate to heavy voice use. The type of training that a singer possessed was the categorical variable that appeared to be most closely related to the vocal fold pattern exhibited. Five out of 5 singers who demonstrated a dynamic pattern were trained classically in a University at a BMus or MMus degree level (E1, E4, E8, E12, E13). Three out of 4 singers who demonstrated a static pattern were trained in musical theatre at a community college (E5, E9, E10), and 1 singer was trained classically at the PhD level (E6).

DISCUSSION

The predominant new finding from this study is the existence of two patterns of pitch control exhibited by singers. It can be inferred that the use of a static pattern of vocal fold length change is associated with isometric contractions and a dynamic pattern of vocal fold length change is associated with isotonic contractions. The discovery that the type of contraction exhibited by trained singers is most related to the number of years of training raises the question of whether less experienced vocal athletes tend to use isometric contractions and then switch to using isotonic contractions as they become more proficient. Sports research in other areas such as soccer[29] and karate[30] indicate that the number of years of training has a significant effect on skill level. Therefore, it may be that the use of isotonic contractions is of a higher skill level than the use of isometric contractions, and that more years of training eventually lead to the predominant use of isotonic contractions to accomplish pitch change. However, a previous study comparing trained singers to nonsingers indicated that nonsingers tended to show more elongation of the vocal folds per one semitone increase than singers[4], implying that nonsingers were using more isotonic contractions to accomplish pitch change than singers. This contradicts the idea that the use of isotonic contractions is a manifestation of a higher skill level. Nevertheless, it may not be appropriate to compare data from this previous study[4] to the present study, as the measurement techniques and participant characteristics vary greatly between the studies.

It also has been shown that more vocal fold length change is observed in the lower singing register, and that in the higher singing register, little length changes[4] and even decreases in length occur in conjunction with pitch increase[5]. The results from the present study demonstrating the use of isometric versus isotonic contractions between two groups of singers can only be applied to the chest voice, or lower singing register, as this was the pitch range used in the production of the scales. It is likely, given the previous evidence, that this same dichotomy would not exist in the same manner at a higher pitch range.

The type of training possessed by the singers also was of interest as it differed between the two groups, leading to the question of whether isometric contractions are more suited for musical theatre, and isotonic contractions more suited to classical singing. Because the singers that were trained in musical theatre also possessed fewer years of training than the classically trained group in this study, it was impossible to ascertain whether the type of contraction used had more to do with the type of training or the number of years of training, or if it was a combination of both.

Two participants in this study experienced vocal fatigue, and it is noteworthy that one of them exhibited a static pattern and the other exhibited a dynamic pattern. A previous study of typical voice users[23] demonstrated that isometric vocal fold contractions (static pattern) were used by speakers with vocal fatigue and isotonic contractions (dynamic pattern) were used by speakers without vocal fatigue. The notion that vocal fatigue could be associated with isometric contractions stems from evidence of fatigue in other muscles of the body, such as knee extensor muscles where prolonged isometric contraction was associated with rapidly occurring muscle fatigue[31]. This fatigue in isometric contractions was due to the accumulation of metabolites, whereas isotonic contractions maintain blood flow that removes the accumulation of metabolites.

Because only two of the participants in the present study exhibited signs of fatigue, conclusions cannot be made regarding the physiological adjustments related to those reports of fatigue. However, it appears that the type of contraction used in singers does not relate to the presence or absence of vocal fatigue the way it does in typical voice users. The connection between isometric contractions and the presence of vocal fatigue and the connection between isotonic contractions with the absence of vocal fatigue in typical voice users can not be assumed for the trained singing voice from these results. If vocal fatigue is indeed not associated with the use of isometric contractions in singers, the question remains: what kinds of adjustments, whether laryngeal or extralaryngeal, are associated with vocal fatigue in professional voice users? This issue needs to be further explored in future investigations with larger participant numbers who have variable types and years of training, and who present with and without symptoms of vocal fatigue.

In terms of respiratory behaviour, lung volume excursions during the production of scales were comparable to previous reports indicating that trained singers tend to initiate breath groups at higher lung volumes and encompass large ranges of %VC[16,32]. Although not statistically significant, the variability in maximum and minimum %VC during scale production between the groups appeared to be different as can be seen in comparisons of the boxplots (Figure 9) and standard deviations. The static group exhibited a greater range in terms of maximum and minimum %VC, while the dynamic group exhibited a smaller range. There appears to be a trend where singers exhibiting isometric or static vocal fold contractions are more dynamic in %VC use, while singers exhibiting isotonic or dynamic vocal fold contractions are more static in %VC use. This provides evidence that there may be an interaction between the various subsystems to accomplish pitch change, and that there may be several strategies available in terms of how the subsystems work together. By exploring this trend, it could be hypothesized that variability or dynamic behaviour in one system leads to stability or static behaviour in the other. In light of this evidence, it would appear that isotonic vocal fold contractions are not necessarily of a higher skill, or are more desirable, than isometric contractions.

Instead, they are two strategies that, when combined with complementary respiratory strategies, accomplish the same goal of pitch change. As the vocal fold patterns were associated with participants' type of training, musical theatre versus classical, it is possible that there exist other interactions of strategies for other types of singing.

With regards to measured vital capacities, the dynamic group appeared to demonstrate larger measured vital capacities than the static group, which exhibited a wider range of vital capacities that included some that could be considered to be in the low end for the vocal athlete. This may be an indication that more years of training and/or classical training lead to a more finely tuned vocal athlete resulting in a larger vital capacity, however previous research has not shown a correlation between an increase in vital capacity and number of years of singing experience[33]. There is some evidence to suggest that singers in general show greater measured than predicted vital capacities[33], and similar findings have been shown in wind instrument players[34]. However, studies comparing singers and wind-players to untrained subjects have not shown differences in vital capacity between groups[35-36]. In considering sports athletes, some studies have shown that when comparing soccer, basketball and volleyball players[37], swimmers[38-39], and older endurance-trained athletes[40] to untrained subjects, athletes exhibited larger vital capacities than controls. However, other studies comparing athletes to controls demonstrate no significant differences in vital capacities[40-41]. Thus it seems unclear whether athletes, in the realm of singing, wind-instrument playing or sports, indeed exhibit larger vital capacities due to their training; therefore the association of larger vital capacities with the dynamic group in this study cannot necessarily be attributed to the increased number of years of training. Furthermore, in the present study, height and weight were not taken for each participant, thus a comparison could not be made between their measured vital capacities and their predicted vital capacities.

The intention of taking surface EMG data was to observe whether there was a difference in activation patterns in rest versus singing, which may have demonstrated activation of supralaryngeal musculature controlling laryngeal height for pitch change. However, when EMG signal frequencies were analyzed, a postural tremor was found during the rest condition, similar to a physiological tremor found in limb extension of fingers, hand and leg muscles in normal individuals[27]. This was likely evoked by the participant's position of having her mouth open wide and her tongue pulled out during the rest condition, as postural tremor has been demonstrated when proximal muscles are maintaining a posture[27]. This postural tremor was exhibited in all singers during rest and disappeared in the singing condition, presumably because the singers were able to override the tremor based on motor commands and aeromechanical drive to sing. The presence of the postural tremor was likely related to EMG amplitudes generally staying the same in rest and singing conditions. In future studies, it would be necessary to produce rest and singing conditions where the postural tremor would not be evoked, where the participant could sit with the mouth closed for rest and then sing without the encumbrance of the rigid scope for the singing condition.

Other findings in this study based on comparison of the two groups have also proven interesting. Observed differences between the groups on scores for the VHI were informative. The scores on the Functional scale were associated with the number of years of training. The dynamic group (who had more years of training) scored higher on the Functional subscale than the static group, indicating that the two groups perceive their vocal apparatus in different ways. For example, individuals in the dynamic group were more likely to respond positively to statements such as "I run out of air when I talk" or "My voice difficulties restrict my personal and social life". Research into psychological factors in sports athletes suggests that elite athletes such as Olympic gold medalists exhibit perfectionistic tendencies that allow them to succeed[42]; this may be a parallel to the higher scores on the Functional subscale in the dynamic group. Theoretically, the accelerated nature and degree of training in the dynamic group that has the potential to result in perfectionistic tendencies may lead those individuals to be more critical of their vocal function than those in the static group. It is also interesting that given the lower scores on the Functional subscale, the static group then demonstrated higher and more variable scores on the Physical subscale. For example, individuals in the static group were more likely to respond positively to statements such as "The sound of my voice varies throughout the day" and "I feel as though I have to strain to produce voice". This response pattern in the static group indicates that there may be some discord between the physical health of their voices and perceptions of their vocal function. The dynamic group, in contrast, scored in a much smaller range and tended to be lower on the Physical subscale, indicating that though they were more critical of their vocal function, physically their voices were working well. The lower scores on the Physical subscale in the dynamic group may be a reflection of their higher vocally athletic ability. However, contrary to these findings, a previous study has shown that classical singers tend to score lower than nonsingers on the total VHI, score higher on the Emotional subscale, lower on the Functional subscale, and highest on the Physical subscale[43]. It was also found that classical singers scored lower overall compared with musical theatre singers[43]. Because of the small number of participants in the present study, the results need to be interpreted with caution in light of these previous findings.

The results of the correlation analysis demonstrated logical links between variables. The participants were asked to start singing the scales in a comfortable pitch in their chest voice, so it stands to reason that the start and end pitches correlate with their fundamental frequencies for speech. It is also logical that the participants' use of vital capacity in the production of scales was correlated with their measured vital capacity. Finally, it is reasonable that the number of years of training was correlated with age, as older participants would likely have more years of training.

Because of the small sample size in this study, significant differences found between the two groups need to be interpreted with caution and cannot be generalized. However, the discovery of two different patterns of vocal fold behaviour existing in these singers indicates that there are indeed different ways to accomplish the same changes in pitch, and that these different patterns may be based on years of experience and/or training. Further studies need to be conducted with higher numbers of singers with various types and years of training, as well as singers with and without vocal fatigue, in order to determine what factors are responsible for different physiological adjustments for pitch change.

APPENDIX A

VOCAL QUESTIONNAIRE

Subject Code: _______________ Date of Completion: ___________________

SECTION I

CURRENTLY EXPERIENCE OR HISTORY OF THE FOLLOWING: (circle yes or no; y/n)

Laryngeal/throat surgery: y / n; type_______________ when________

Traumatic injury to the larynx/throat: y / n; type_______________ when________

Medically diagnosed:

Neurological disorder: y / n; type_______________

Neuromuscular disorder: y / n; type_______________

Congenital (from birth) laryngeal/voice disorder: y / n; type_______________

Organic voice disorder (e.g., polyps, nodules, etc.): y / n; type______ when______

Psychological disorder: y / n; type_______________ when________

Swallowing disorder: y / n; type________ when________

Gastro-esophageal reflux disease: y / n; when___ current/previous medication_____

Hormone imbalance/disorder: y / n; when____ current/previous medication______

Underwent/undergoing:

Hormone therapy: y / n; when________ what kind___________ how long________

Voice therapy: y / n; when________ where_________________ how long________

More than one year of professional vocal/theatrical training: y / n

Current prescription or over-the-counter medication: y / n type(s) _______________

____

Tobacco Use : y / n; If yes, How many years_____ Current packs/wk_____

If < 1 pack, cigarettes/wk________

If you have quit how many years since you have last smoked______

Alcohol use: How many 8 oz. glasses/day_____ How many 8 oz. glasses/wk_______

Consistently used alcohol in any way other than mild casual use: y / n

Water intake: How many 8 oz. glasses/day________

Miscellaneous: (Check all that occur at least 4/7 days per week)

Eat before bed________ Eat spicy food________ Use a humidifier________

SECTION II

OCCUPATION(S): (if student list major field of study plus any jobs) __________

____

Singing voice use (include practice/rehearsal times as well as performances):

per day (check one of the following):

mild (0 to 3 hrs.)____ moderate (3+ to 6 hrs.)____ heavy (6+ hrs.) ____

Hours/day at work/school_______ Percentage of time using voice_______

Type of singing (check all that apply):

☐ Choral (where __________________) ☐ Solo (where ______________________)

☐ Classical (where _________________) ☐ Opera (where ______________________)

☐ Musical Theatre (where ___________) ☐ Pop/Rock/Jazz (where ______________)

Voice use for occupation/student: per day (check one of the following):

mild (0 to 3 hrs.)____ moderate (3+ to 6 hrs.)____ heavy (6+ hrs.) ____

Hours/day at work/school_______ Percentage of time using voice_______

All other voice use: (voice use outside of school or work- remainder of your day)

mild (0 to 3 hrs.)____ moderate (3+ to 6 hrs.)____ heavy (6+ hrs.) ____

Hours/day outside of work/school______ Percentage of time using voice_______

Speaking over background noise (e.g., music, customers, machines, children, etc.):

yes____ no____ if yes, describe____

____

SECTION III

RECREATIONAL/ADDITIONAL ACTIVITIES: (check all that apply and list hours per week)

Activity — Hours per week on average

☐ Cheerleading____ ______

☐ Sports participant[list sport(s)]_______________________________ ______

☐ Sports spectator [list sport(s)]_______________________________ ______

☐ Sports coach [list sport(s)]__________________________________ ______

☐ Primary caretaker for child(ren)____ How many kids________ ______

☐ Supervise children (e.g., babysitting, scouts, etc) How many kids_____ ______

☐ Attendance at bars, clubs/discos, pool halls, house parties, etc. ______ ______

Other activities (please list) with moderate (3+ to 6 hrs) to heavy (6+ hrs) voice use:

Activity____

Activity____

Activity____

SECTION IV

DURING ANY TIME OF YOUR LIFE, HOW DOES YOUR VOICE, THROAT AND/OR NECK FEEL AFTER MODERATE (3+ TO 6 HRS) TO HEAVY (6+ HRS) VOCAL USE: (check all that apply)

normal____ sore/painful____ warmed up____ scratchy____ improved____

strained____ strong____ stressed____ fine____ effortful____ powerful____

At any time in the past I have experienced any of the above symptoms:

more than 1x/day____ 1x/day____

if per week; specify # of days ____ if per month; specify # of days ____

I currently experience any of the above symptoms:

more than 1x/day____ 1x/day____

if per week; specify # of days ____ if per month; specify # of days ____

Whenever I have experienced these symptoms they have lasted for:

under an hour____ a couple of hours ____ all day____ if > 1 day; specify #____

DURING ANY TIME OF YOUR LIFE HOW HAS YOUR VOICE SOUNDED AFTER MODERATE (3+ TO 6 HRS) TO HEAVY (6+ HRS) VOCAL USE: (check all that apply)

unchanged____ hoarse____ stronger____ breathy____ improved____ rough____

clear____ tense____ higher pitched____ lower pitched____ same pitch____

decreased in pitch range____ increased in pitch range____ decreased volume/power____ increased volume/power____ decreased vocal control____ increased vocal control____ effortful____

At any time in the past I have experience any of the above symptoms:

more than 1x/day____ 1x/day____

if per week; specify # of days ____ if per month; specify # of days ____

I currently experience any of the above symptoms:

more than 1x/day____ 1x/day____

if per week; specify # of days ____ if per month; specify # of days ____

Whenever I have experienced these symptoms they have lasted for:

under an hour____ a couple of hours ____ all day____ if > 1 day; specify #____

(adapted from McCue[23])

APPENDIX B

TELEPHONE SCREENING

Date message received: ________________ Date screened: ____________________

Contact Information: ____

1. MALE FEMALE
2. AGE ______
3. VOICE QUALITY: NORMAL MILDLY DYSPHONIC DYSPHONIC
4. HISTORY OF:

▪ laryngeal surgery	Y	N
▪ traumatic injury to the larynx	Y	N
▪ voice disorder	Y	N
▪ emotional/physical disease requiring treatment	Y	N
▪ menopause	Y	N
▪ voice therapy	Y	N
▪ smoking within the last 5 years	Y	N

▪ current use of prescription drugs

____

____

5. Has been training in singing for ______ years.

Level and type of training (professional, college, private) ____________________

____

Approximately how many hours a week do you sing now? _________________

6. Invite to screening session Y N

Date: _________________________Time: ____________________________

(adapted from McCue[23])

APPENDIX C

VOICE HANDICAP INDEX[25]

Subject code: ____________________________ Date of Completion: __________

These are statements that many people have used to describe their voices and the effects of their voices on their lives. Write the number associated with the response that indicates how frequently you have the same experience:

Response Key:

0 = Never
1 = Almost Never
2 = Sometimes
3 = Almost Always
4 = Always

_____ F1. My voice makes it difficult for people to hear me.
_____ F2. I run out of air when I talk.
_____ F3. People have difficulty understanding me in a noisy room.
_____ P4. The sound of my voice varies throughout the day.
_____ F5. My family has difficulty hearing me when I call them throughout the house.
_____ F6. I use the phone less than I would like.
_____ E7. I'm tense when talking with others because of my voice.
_____ F8. I tend to avoid groups of people because of my voice.
_____ E9. People seem irritated with my voice.
_____ P10. People ask, "What is wrong with your voice?"
_____ F11. I speak with friends, neighbours, or relatives less often because of my voice.
_____ F12. People ask me to repeat myself when speaking face-to-face.
_____ P13. My voice sounds creaky and dry.
_____ P14. I feel as though I have to strain to produce voice.
_____ E15. I find that other people don't understand my voice problem.
_____ F16. My voice difficulties restrict my personal and social life.
_____ P17. The clarity of my voice is unpredictable.
_____ P18. I try to change my voice to sound different.
_____ F19. I feel left out of conversations because of my voice.
_____ P20. I use a great deal of effort to speak.
_____ P21. My voice is worse in the evening.
_____ F22. My voice problem causes me to lose income.
_____ E23. My voice problem upsets me.
_____ E24. I am less outgoing because of my voice problem.
_____ E25. My voice makes me feel handicapped.
_____ P26. My voice "gives out" in the middle of speaking.
_____ E27. I feel annoyed when people ask me to repeat.
_____ E28. I feel embarrassed when people ask me to repeat.
_____ E29. My voice makes me feel incompetent.
_____ E30. I am ashamed of my voice problem.

APPENDIX D

ACOUSTIC ANALYSIS

Subject Code: ________________ Date of Assessment: ________________

1. **Maximum Phonation Time (MPT) of "ah":**

***Trial 1:* ________ *Trial 2:* ________ *Trial 3:* ________ *MPT =* ________**

2. **S/Z Ratio:**

/s/: Trial 1: ________ Trial 2: ________ Max. /s/ = ________

/z/: Trial 1: ________ Trial 2: ________ Max. /z/ = ________

S/Z Ratio = ________

3. **Fundamental Frequency:**

/a/: Trial 1: ________ Trial 2: ________ Trial 3: _______ Avrg.fo /a/ = ________

10 seconds of spontaneous speech (fo speech):

Trial 1: ________ Trial 2: ________ Trial 3: _______ Avrg.fo /speech/ = ____

Perceptual voice quality: breathy rough tense normal

(adapted from McCue[23])

APPENDIX E

PILOT STUDY

The methods used in this study were derived from pilot work which addressed data acquisition and measurement issues. As there is presently no established protocol for investigating and measuring vocal fold length change and the possible relationship to respiratory behaviour, vocal fold and respiratory data were taken from four pilot participants in order to develop a suitable protocol for data acquisition as well as a valid measurement protocol. Four healthy and vocally untrained female participants, between the ages of 23 and 47 years old, were tested. These participants were all from the Speech Pathology and Audiology Department at the University of Alberta.

Pilot Study: Vocal Fold Measurement

The measurement protocol for this study was modified from that used in McCue[23]. In McCue's study, the vertical length of the vocal folds was measured along the medial edge of the left vocal fold between the posterior and the most anterior portion visible, using the anterior commissure if possible (see Figure 10). The horizontal length, assumed to be constant, was measured between the lateral edges of the epiglottis, either between the points along the lateral edges of the epiglottis where the shape changed from a concave to a convex curve, or between the points where the aryepiglottic folds inserted onto the epiglottis. One method of measurement was used consistently across each subject's images in McCue's study.

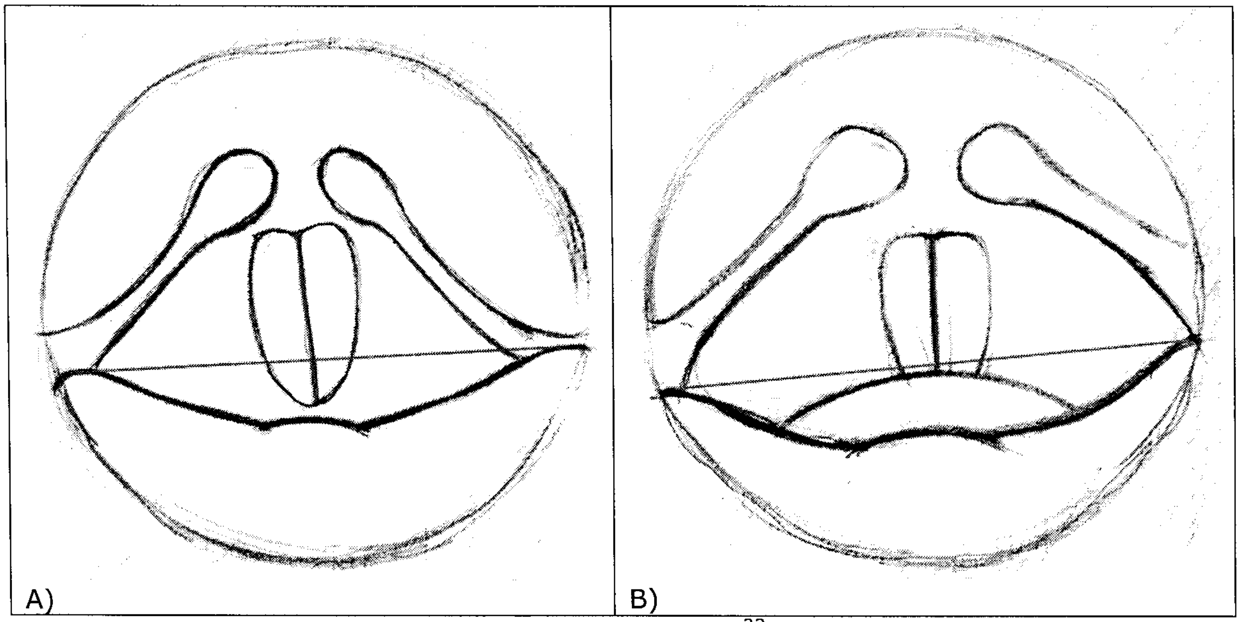


Figure 11. Vocal fold measurement protocol in McCue[23]. Two measurement methods were used, depending on what was visible in the image. A) The vertical length was taken from the posterior to anterior commissures along the medial edge of the left vocal fold. The horizontal length was taken between the two lateral edges of the epiglottis. B) When the anterior commissure was not visible, the vertical length was taken from the posterior commissure to the most anterior point visible along the medial edge of the left vocal fold. The horizontal length was taken between the two lateral edges of the epiglottis.

For pilot participants in the present study, the same measurement protocol was applied as in McCue[23] with the following modifications: a 90 degree angle was applied between the vertical and horizontal lengths, and the horizontal length was taken from the lateral edge of the epiglottis, where the shape changed from concave to convex, to the space between the vocal folds. The landmark for the horizontal length was modified in the present study because of the difficulty in obtaining an image where both sides of the epiglottis were visible. See Figure 11 for a schematic diagram of vocal fold measurement used in the pilot images of the present study.

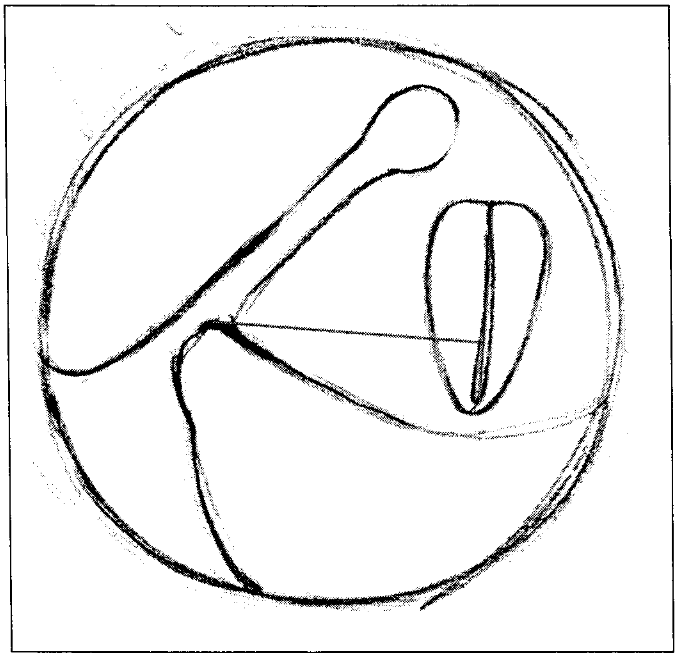


Figure 12. Vocal fold measurement protocol in pilot work of the present study.

McCue[23] used a program called *ImageJ* from the National Institutes of Health (http://rsb.info.nih.gov/nih-image/download.html) for vocal fold measurement. For the present study, a program called *CorelDraw* was used instead, as it allows for more sophisticated measurement options, such as automatic measurement display, the ability to place multiple images in one display so that all images across one scale can be seen at one time, the ability to label images, the capacity to create measurements at exactly 90 degrees from each other, and the ability to adjust a measurement if it was made incorrectly. In order to validate the *CorelDraw* method of measurement, vertical and horizontal lengths were measured on several images from three pilot participants using both *ImageJ* and *CorelDraw*. Figure 12 depicts the ratio of vertical to horizontal lengths in several images from three participants, which indicate that both programs produce virtually the same results. In light of these results, *CorelDraw* was used for this study instead of *ImageJ* in order to allow for easier measurements.

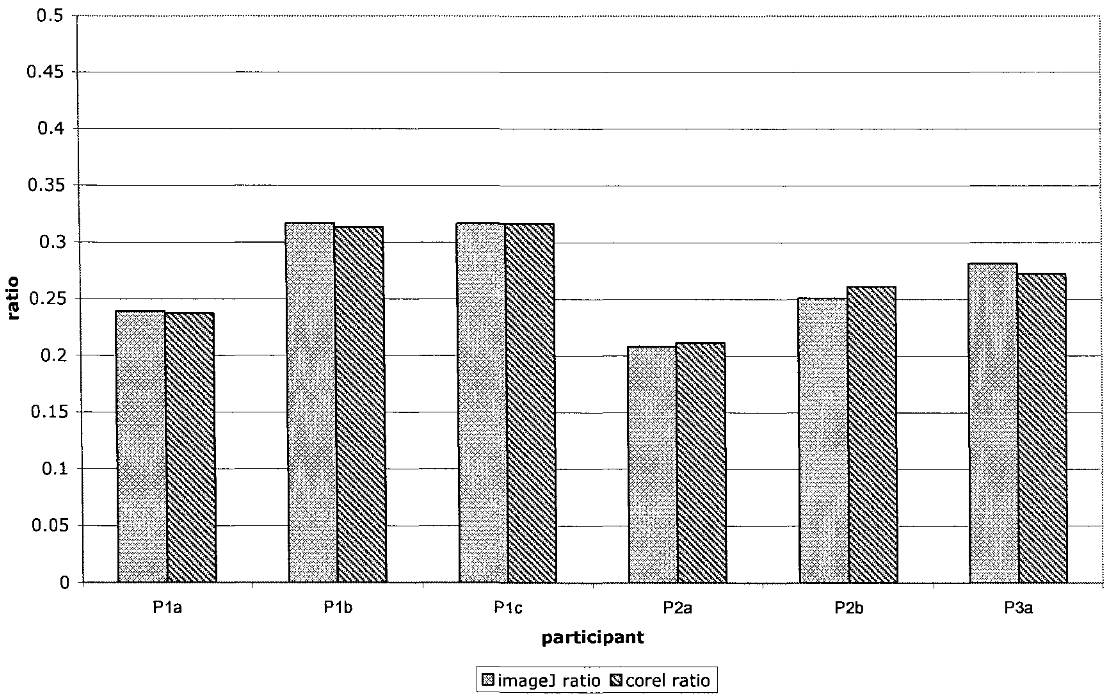


Figure 13. Comparison of ratios obtained in ImageJ and CorelDraw of vertical to horizontal lengths measured on images of vocal folds from three pilot participants.

Pilot Study: Instrument Calibration of the Rigid Endoscope

Because the distance between the endoscope and the participant's vocal folds could not be controlled, a calibration was performed in order to determine the robustness of the vertical to horizontal ratio measurement. This protocol was based on McCue's[23] calibration. Using 2mm graph paper, images were taken of the paper at nine different distances: 7/8", 1 1/8", 1 2/8", 1 4/8", 1 5/8", 2", 2 5/8", 3 5/8", 4 5/8", calculated between the endoscope's camera lens and the paper. The endoscope was mounted to a clamp stand to take the images at the different distances.

The vertical and horizontal lengths from the images were measured across 2 squares in the middle of the image in pixels. In order to further validate the use of *CorelDraw* with the *ImageJ* program, the instrument calibration measurements were performed in both programs, with vertical and horizontal lengths measured in pixels, on the same images. Figure 13 depicts the same image at a distance of 3.8 cm, measured by both programs.

A) *B)*

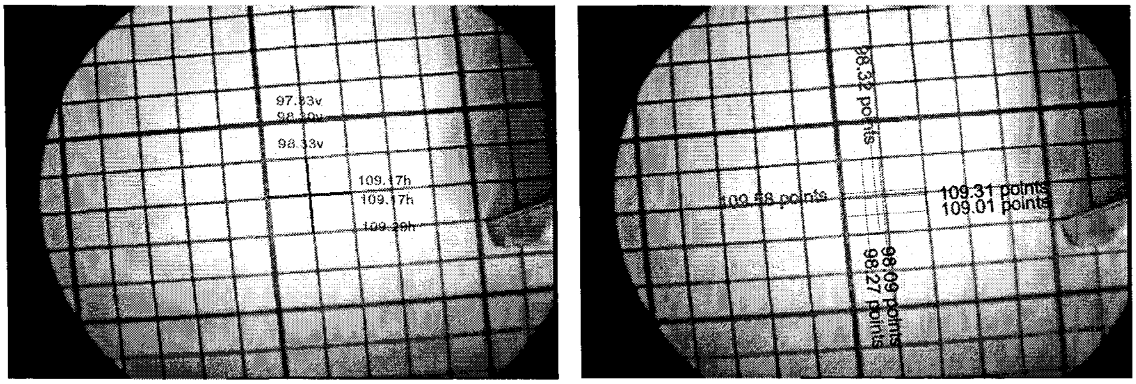


Figure 14. Measurements of horizontal and vertical lengths on an image taken at 3.8 cm away from 2mm graph paper. A) ImageJ measurement in pixels, B) CorelDraw measurement in points.

Measurements were repeated three times on each image, and a ratio of the vertical length to the horizontal length was taken. The mean ratio was then taken from the three trials, at each distance. The mean ratios at each distance are graphed in Figure 14, with the results from both *CorelDraw* and *ImageJ*. It is apparent that the ratios across the distances are constant, and that the results from *ImageJ* and *CorelDraw* are very close, producing virtually the same results.

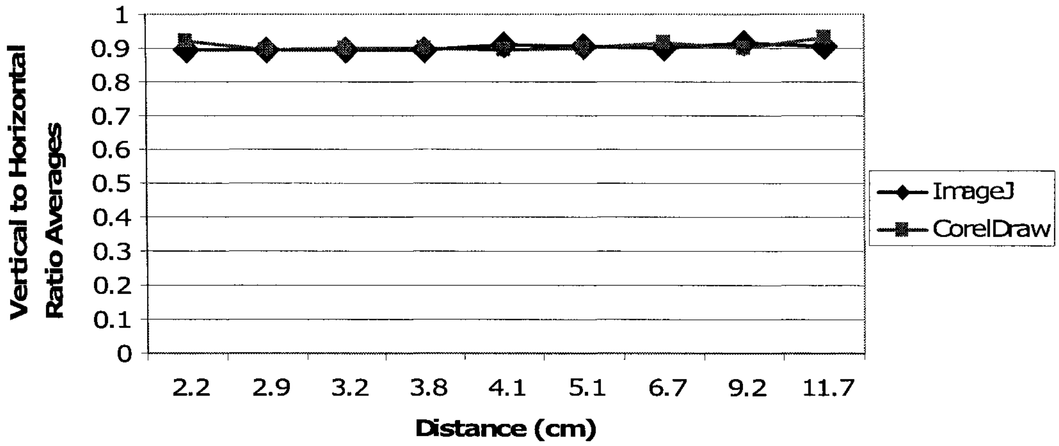


Figure 15. Vertical to horizontal length ratio averages obtained across nine distances in ImageJ and CorelDraw.

A linear model repeated measures analysis (a priori $p < .05$ for significance) was performed on the three trials of ratios at each of the nine distances, for each program. These results are displayed in Table 6. For the within-subjects contrasts, which looked at whether there was a difference between the measures taken across three trials for each distance, there was no significant difference in either the *ImageJ* program or the *CorelDraw* program. For the between-subjects effects, which looked at whether there was a difference in the ratios between distances, there were also no significant differences found using either program. Therefore, the ratio measures were consistent across trials and across distances in both programs.

Table 6. Results of Linear Model Repeated Measures Statistical Analysis for ImageJ and CorelDraw

		F Statistic	**Significance (p < 0.05)**	**Degrees of freedom**
ImageJ analysis	Within-Subjects Contrasts (trials*group)	1.846	0.237	(2,6)
	Between-Subjects Effects (distance)	2.517	0.161	(2,6)
CorelDraw analysis	Within-Subjects Contrasts (trials*group)	0.413	0.679	(2,6)
	Between-Subjects Effects (distance)	2.036	0.211	(2,6)

In order to validate the *CorelDraw* program as an alternative for measurement, a paired-samples t-test was performed on the overall mean ratios of both programs. As is shown in Table 7, there was no significant difference between the two programs.

Table 7. Results of paired-samples t-test for mean ratios of ImageJ and CorelDraw

Paired differences				
mean	**standard deviation**	**t-value**	**significance (2-tailed) (p < 0.05)**	**degrees of freedom**
-0.0035084	0.0151305	-0.696	0.506	8

Paired-samples t-tests were then performed for the *ImageJ* and *CorelDraw* ratios at each of the nine distances; results are shown in Table 8. To avoid familywise error because of the multiple comparisons done with nine t-tests, a Bonferroni correction was used to correct the significance level from 0.05 to 0.005. None of the t-tests demonstrated a significant difference between the two methods of measurement. Thus, it was concluded that *CorelDraw* performed measurements that were no different from those done in *ImageJ*.

Table 8. Results of paired-samples t-tests at nine distances

distance	mean	standard deviation	t-value	significance (2-tailed)
2.2 cm	-0.02215	0.00592	-6.480	0.023
2.9 cm	0.00353	0.01130	0.542	0.642
3.2 cm	-0.00211	0.00944	-0.387	0.736
3.8 cm	-0.00146	0.00416	-0.609	0.604
4.1 cm	0.01422	0.00393	6.271	0.024
5.1 cm	0.00848	0.01084	1.354	0.308
6.7 cm	-0.01434	0.00935	-2.657	0.117
9.2 cm	0.01106	0.00946	2.026	0.180
11.7 cm	-0.02882	0.02341	-2.132	0.167

Pilot Study: Respiratory Data

Respiratory data obtained by Respitrace were analyzed on one pilot participant. The participant exhaled into a hand-held respirometer and the volume recorded over three trials. For each trial, the times corresponding to the beginning of the expiration and the end of the expiration on the waveform were tagged, and the voltage recorded. The difference in voltage between the beginning and end of expiration was then used to correspond to the known volume recorded from the respirometer. A mean was taken of the three voltage differences, and of the three known lung volumes. Figure 15 displays the marking of the beginning and end points of expiration, with the voltage difference corresponding to lung volumes obtained from the respirometer.

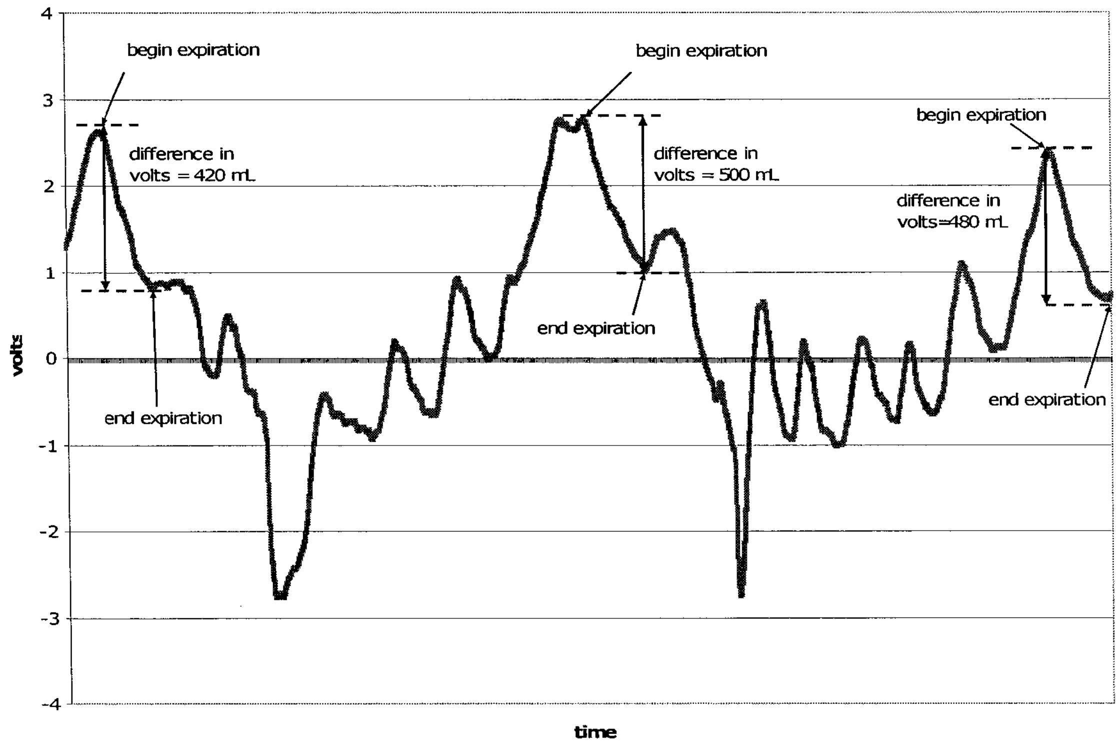


Figure 16. Tidal volume measurement with respirometer in a pilot participant. Beginning and end points of expiration are marked, as is the voltage difference between these two points over three trials.

The mean voltage difference and the mean lung volume were then used to determine the equivalence of mL to 1 volt. This conversion was then applied to the remaining respiratory data in the participant's production of scales. Respiratory analysis for this pilot participant was performed in Excel by exporting a portion of the waveform captured by the KayPentax Swallowing Signals Lab Station in a .txt file.

The difference in voltage between the start of expiration and the end of expiration for the scale allowed for the determination of lung volume used to produce the scale, using the previously mentioned conversion. These two points also allowed for analysis of lung volume for the scale in relation to end expiratory level and tidal volume. The relative lung volumes at each pitch of the scale produced were also obtained, which allowed for comparison relative to end expiratory level, relative to a predicted vital capacity, and relative to the total lung volume excursion. See Figure 16 for an illustration of these measures.

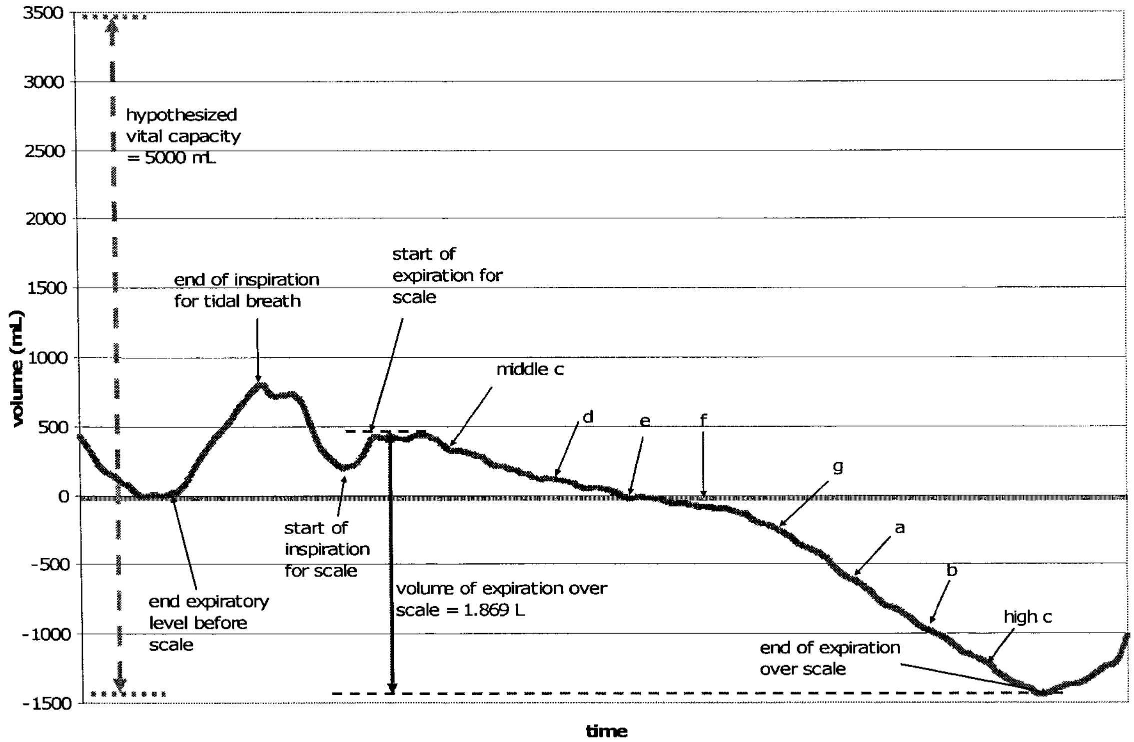
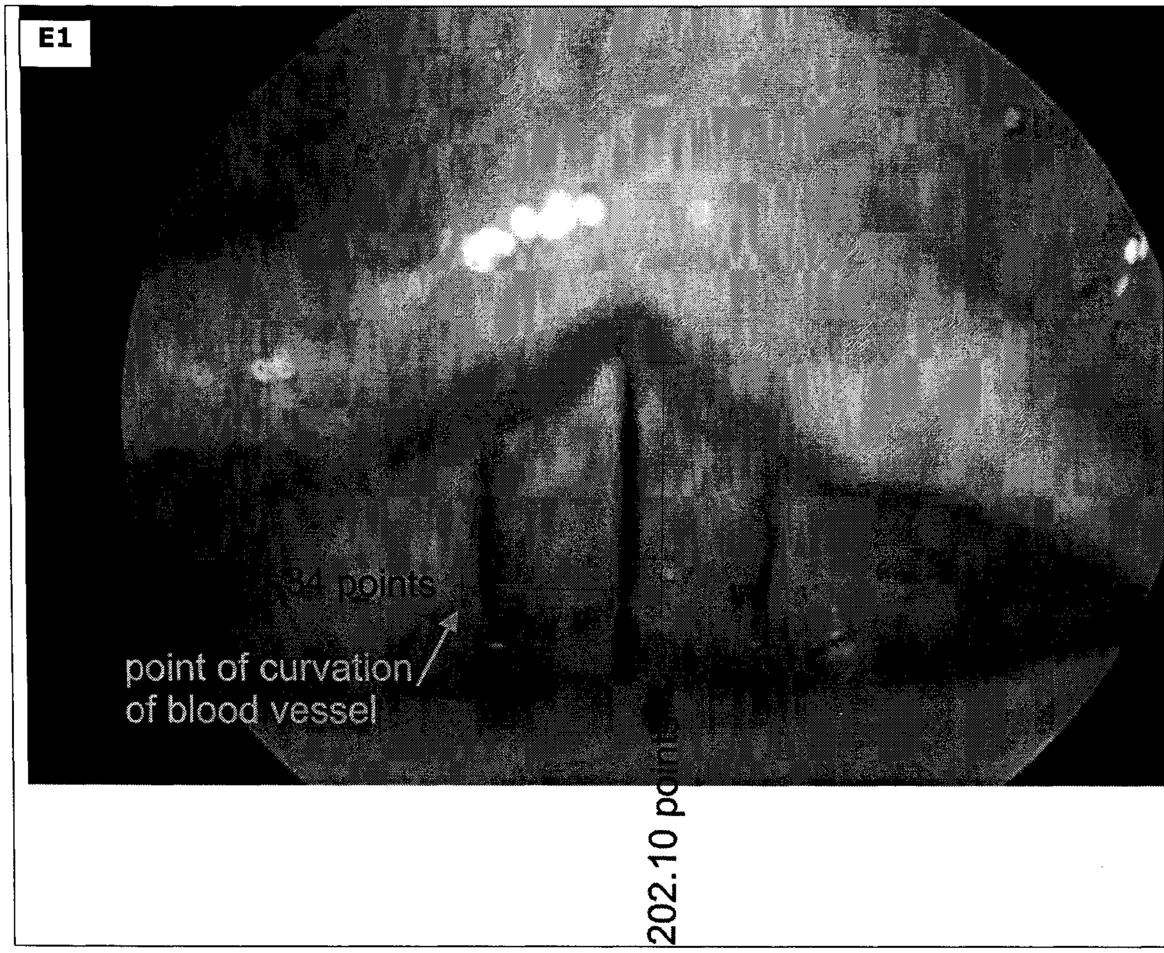
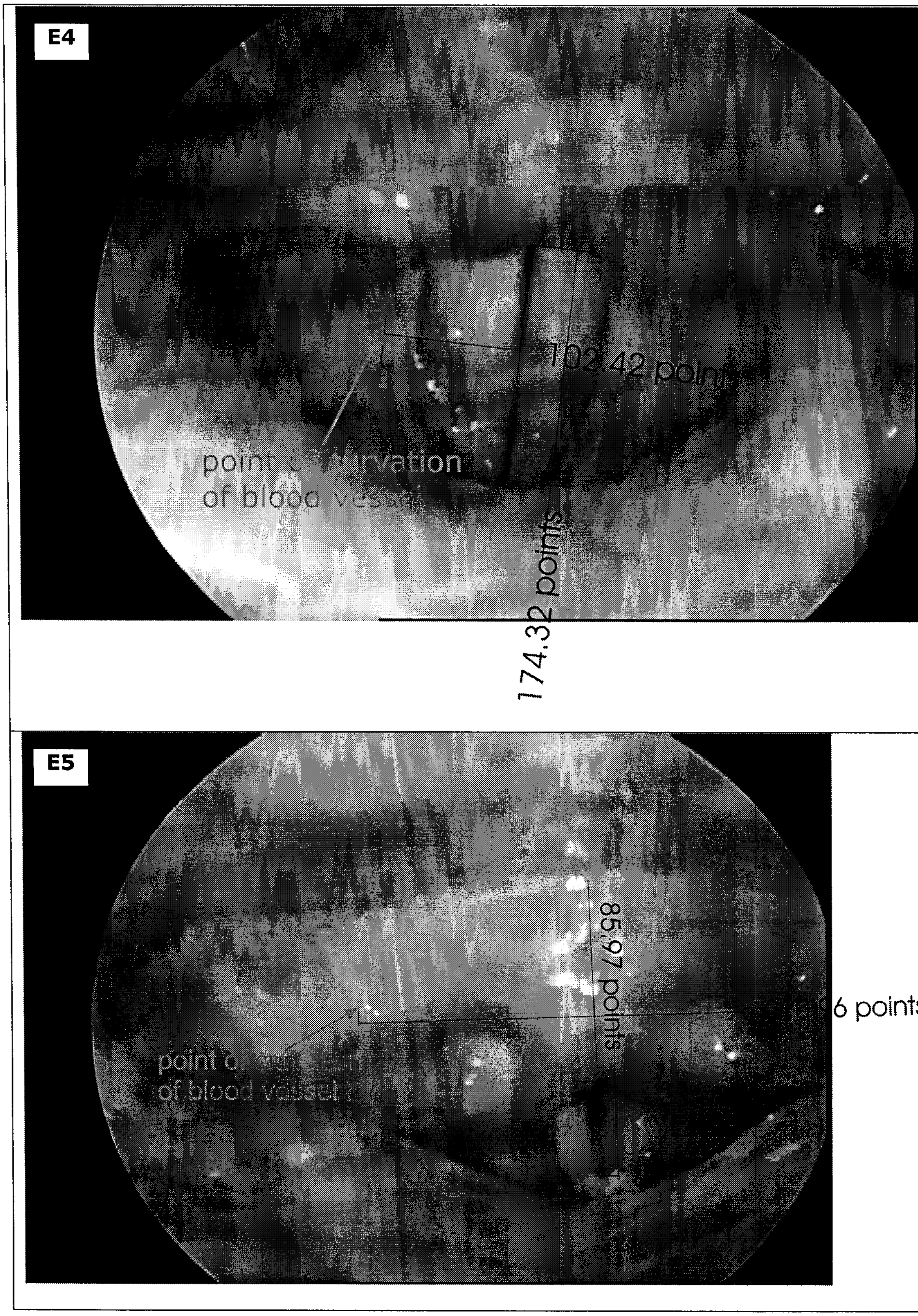


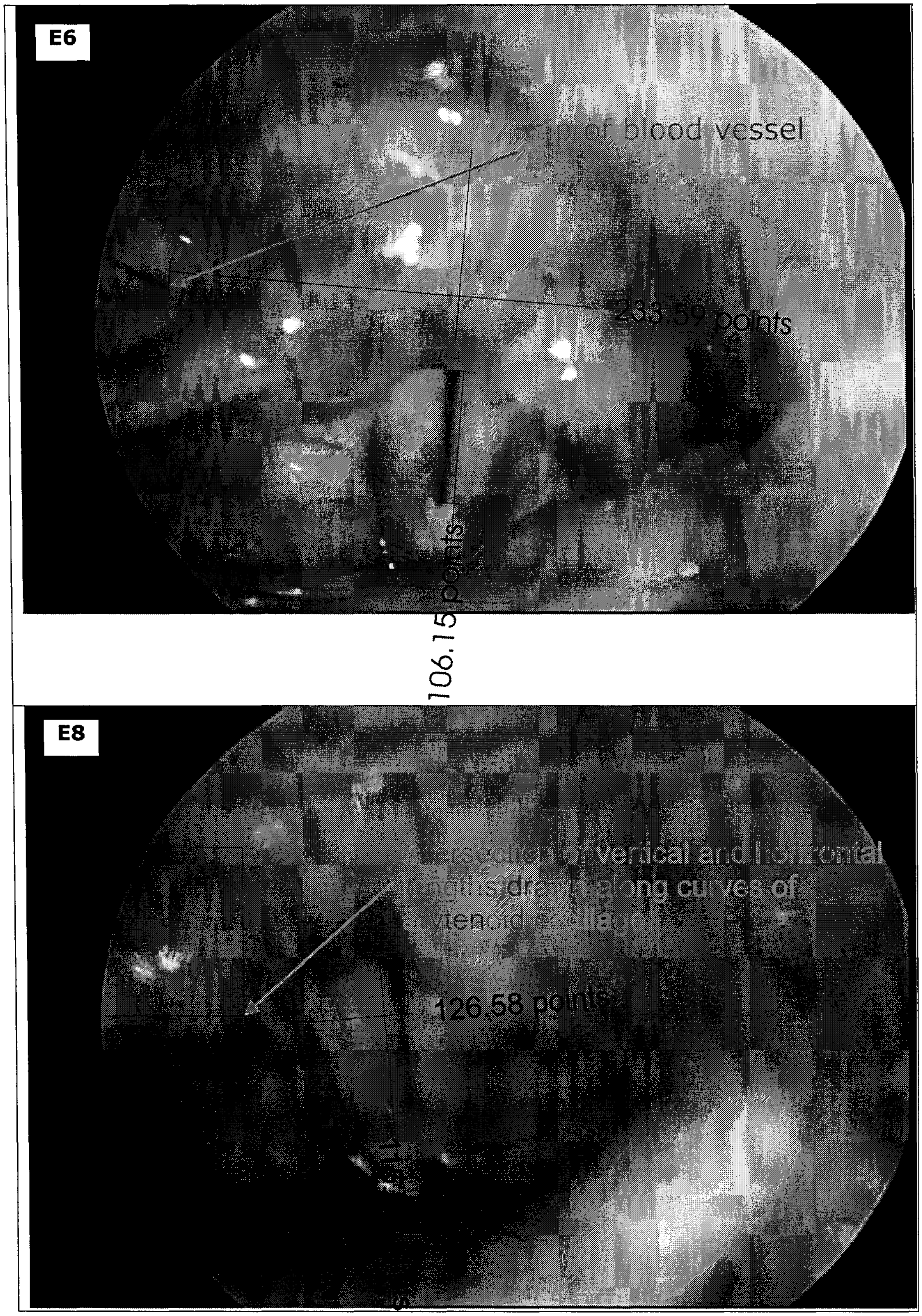
Figure 17. Respiration across an ascending scale in a pilot participant.

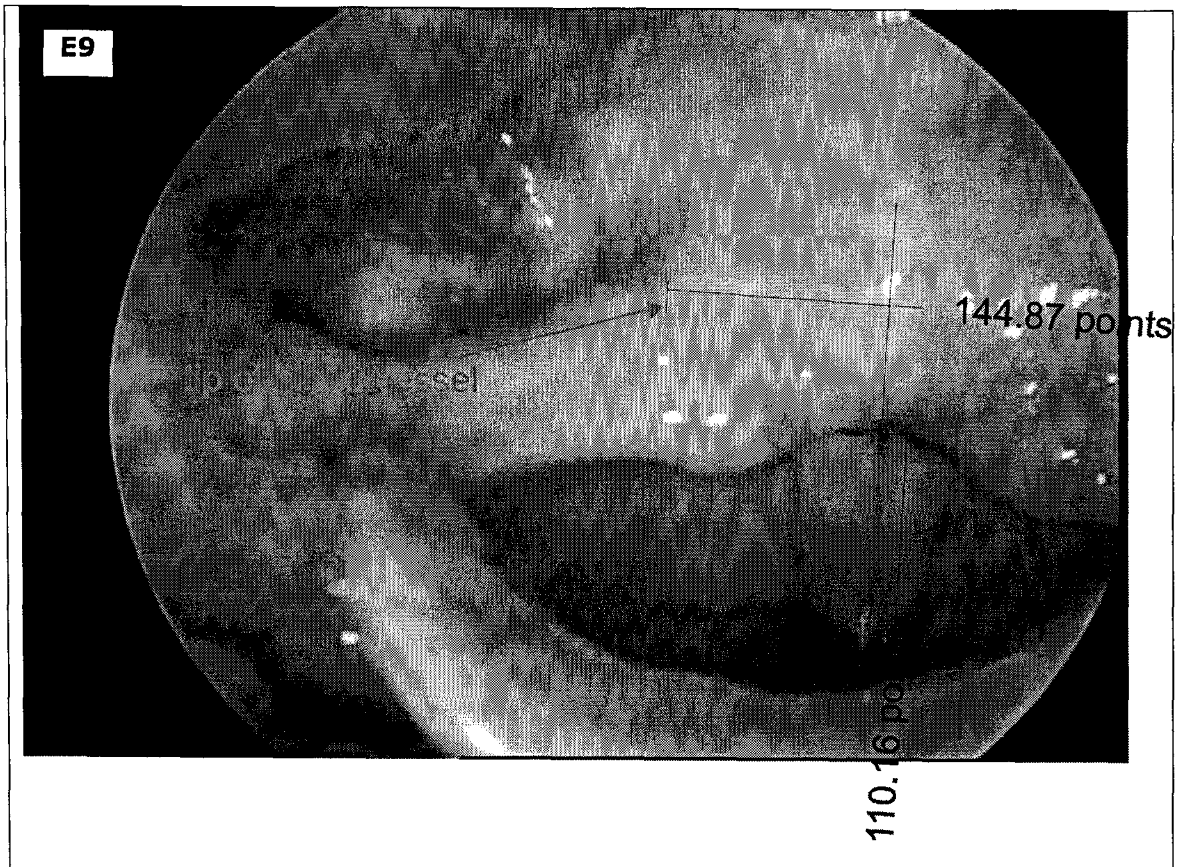
APPENDIX F

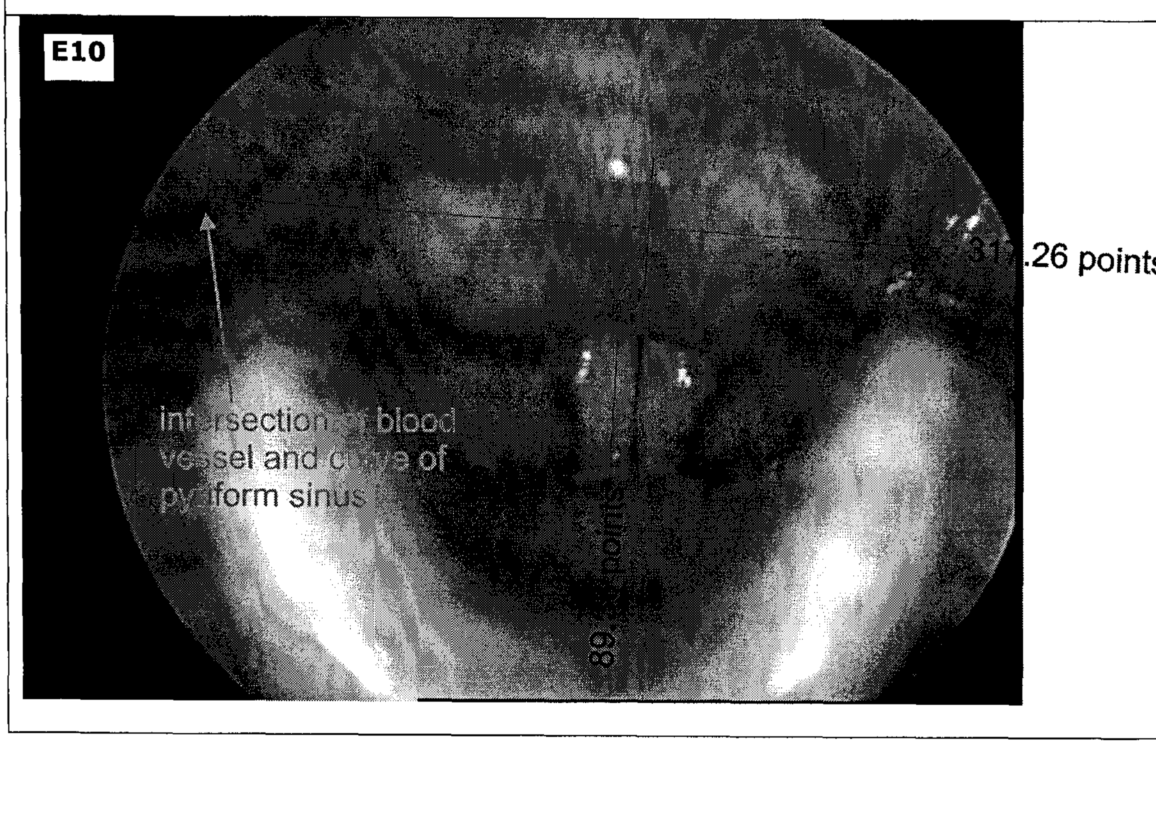
HORIZONTAL LANDMARKS FOR EACH PARTICIPANT




E4
174.32 points
E5
85.97 points


E6
of blood vessel
233.59 points
106.15 points
E8
126.58 points


E9


E10

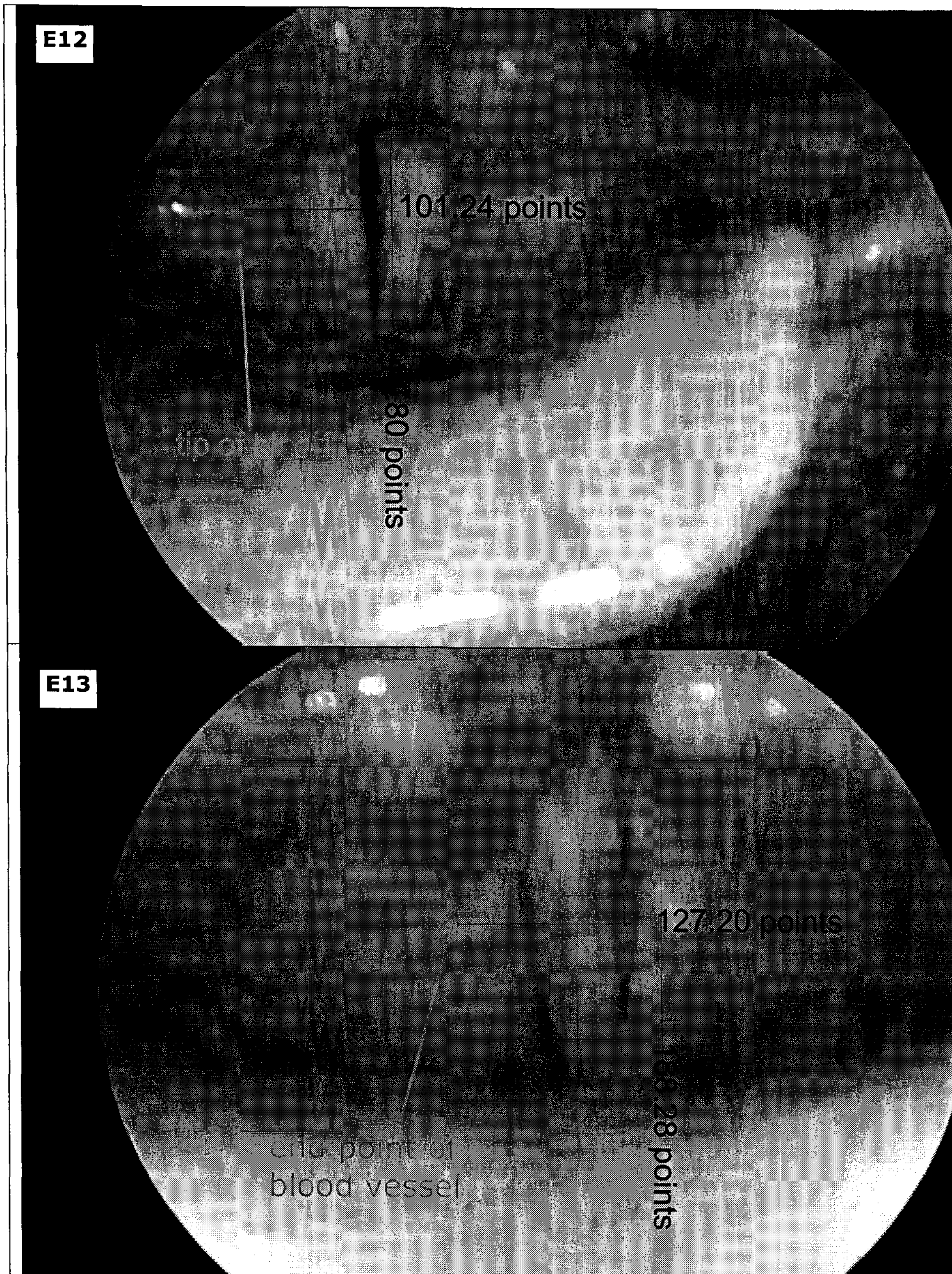


Figure 18. Specific horizontal landmark points for experimental participants. Arrows indicate landmark used for each participant's images.

APPENDIX G

Table 9. Acoustic Analysis Results and Voice Quality Ratings

Participant	Acoustic Analysis				Voice Quality
	MPT (s)	s/z	F_0/a/ (Hz)	F_0speech (Hz)	
E1	20.9	1.17	208.82	210.78	normal
E4	11.14	1.12	214.99	203.38	normal
E5	19.89	1.49	224.64	212.49	normal
E6	15.77	1.24	212.17	180.81	normal
E8	12.44	1.17	226.63	209.87	normal
E9	11.97	1.33	217.82	185.80	normal
E10	15.14	1.03	217.53	210.21	normal
E12	19.74	1.00	202.26	196.91	normal
E13	11.24	0.93	160.97	162.69	normal

APPENDIX H

ADDITIONAL RESPIRATORY DATA

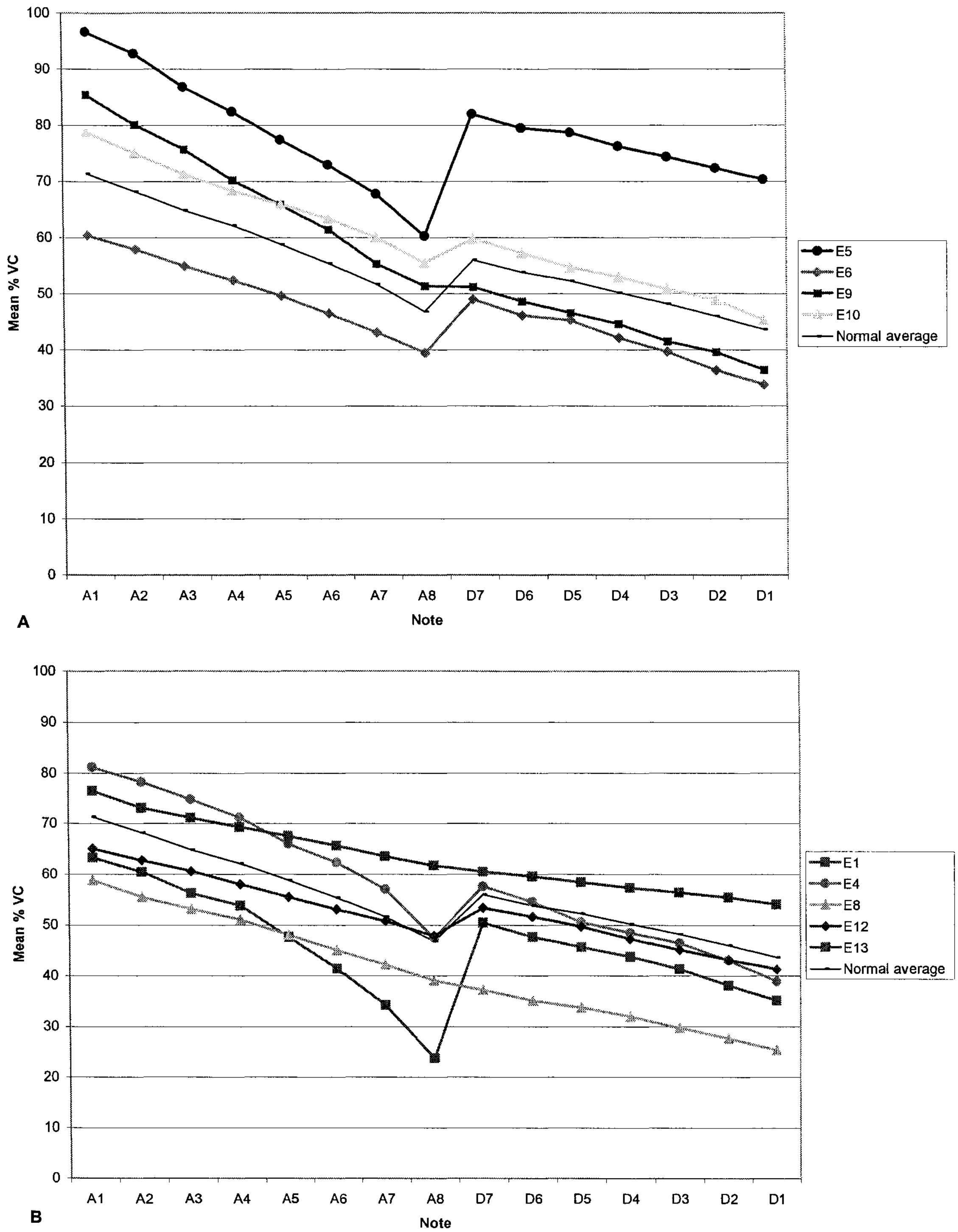


Figure 19. Mean %VC for singers exhibiting static pattern (A) and dynamic pattern (B). The mean percent of vital capacity is displayed on the vertical axis while the horizontal axis displays each note (or pitch) produced in the one octave ascending and descending scales. A1 refers to the lowest note in the ascending scale, A2 to the next lowest note in the ascending scale and so forth up to A8, the highest note in the scale. D7 refers to the next highest note

in the descending scale and so forth until D1, the lowest note in the descending scale. Participants E9 in (A) and participants E8 and E13 in (B) sang an ascending and a descending scale on one breath. Participants E5, E6, and E10 in (A) and E1, E4, and E12 in (B) sang an ascending scale, took a breath, and then sang a descending scale so that two breaths were taken.

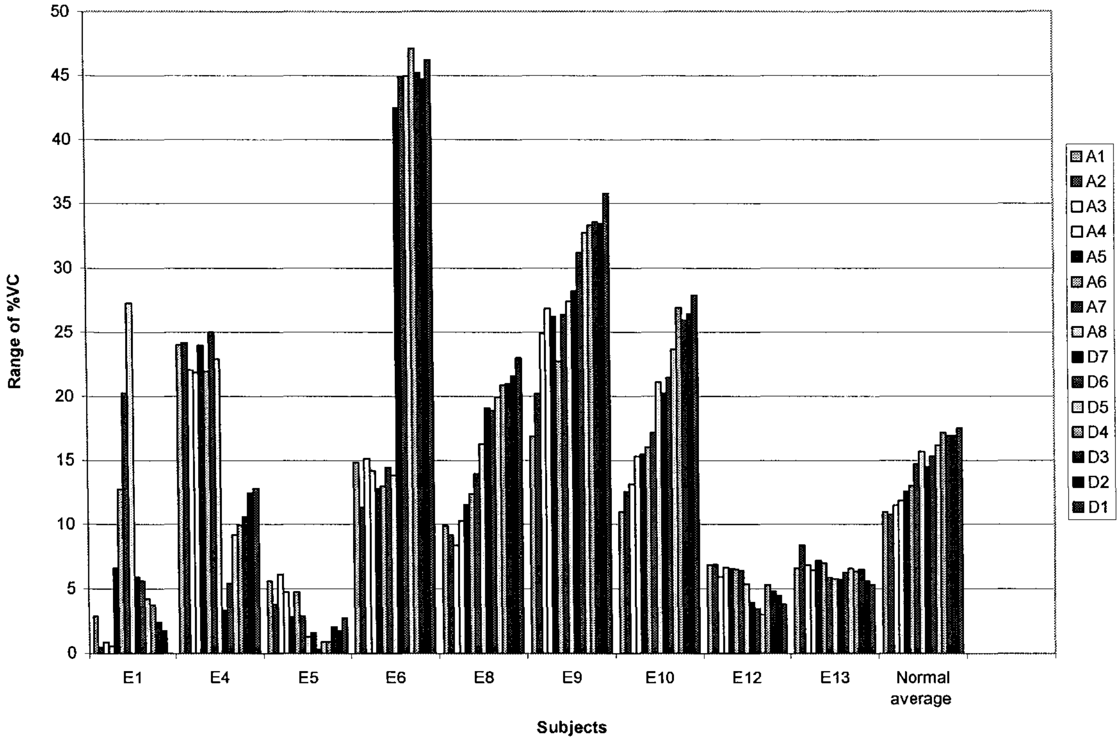


Figure 20. Range of %VC for ascending and descending scales. Normal average is included. The range of values for percent vital capacity for all trials is displayed on the vertical axis while the horizontal axis displays each note (or pitch) produced in the one octave ascending and descending scales. A1 refers to the lowest note in the ascending scale, A2 to the next lowest note in the ascending scale and so forth up to A8, the highest note in the scale. D7 refers to the next highest note in the descending scale and so forth until D1, the lowest note in the descending scale.

APPENDIX I

ADDITIONAL EMG DATA

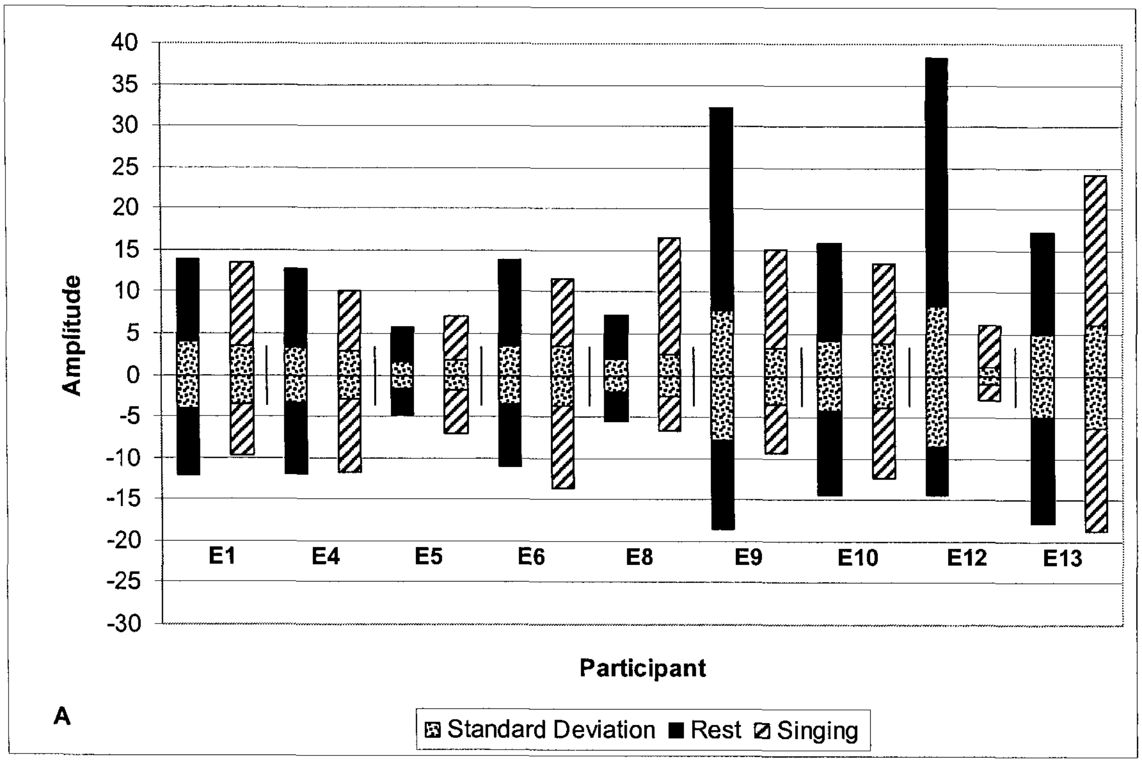
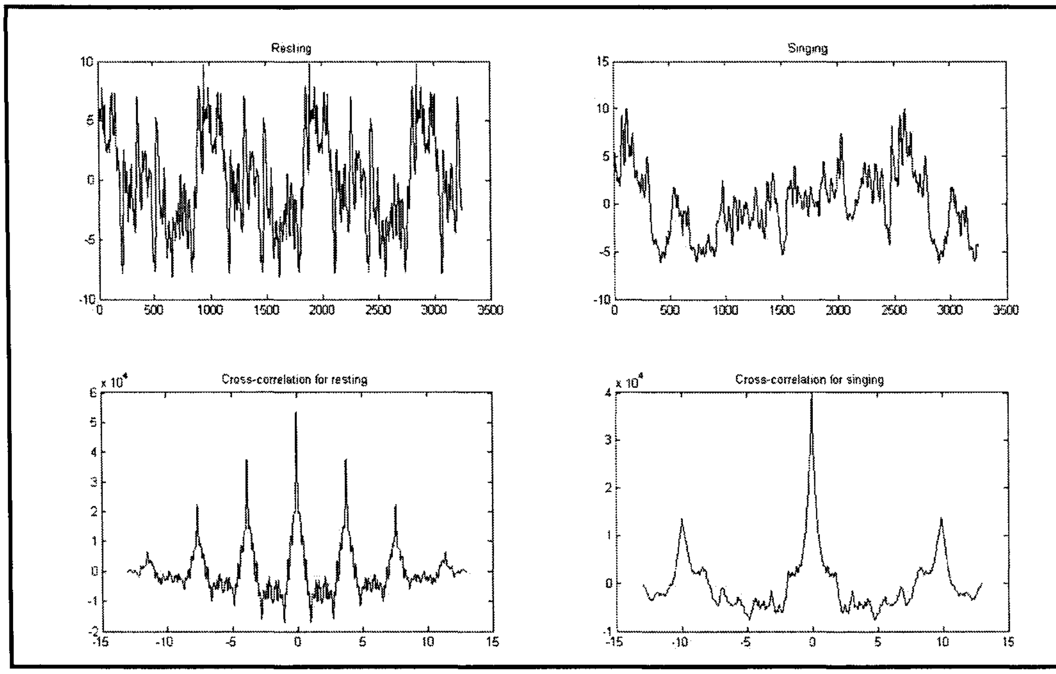
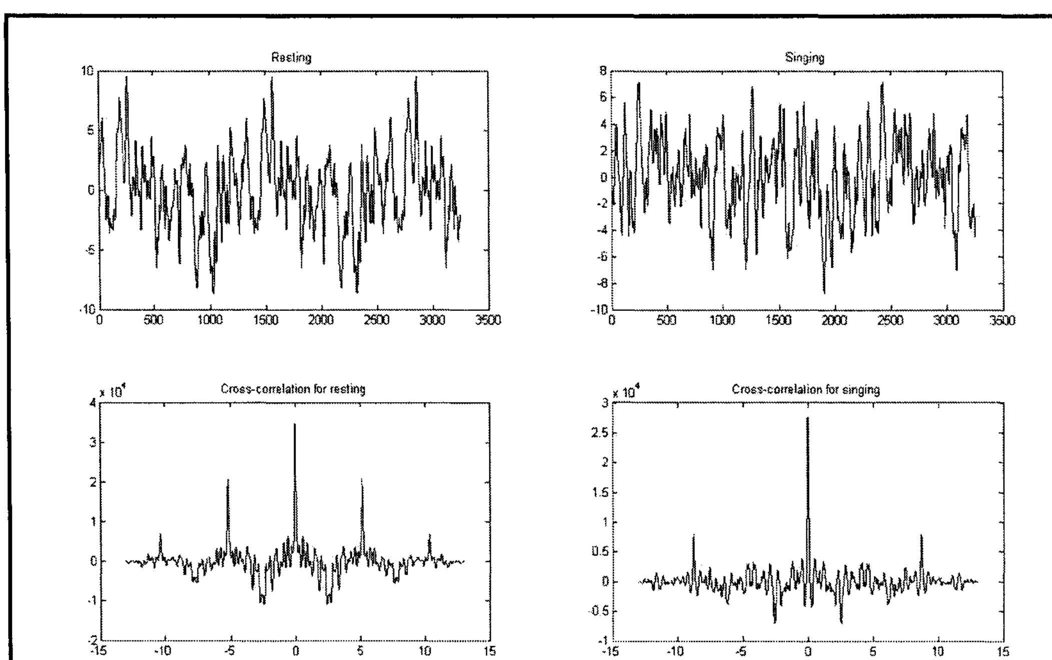


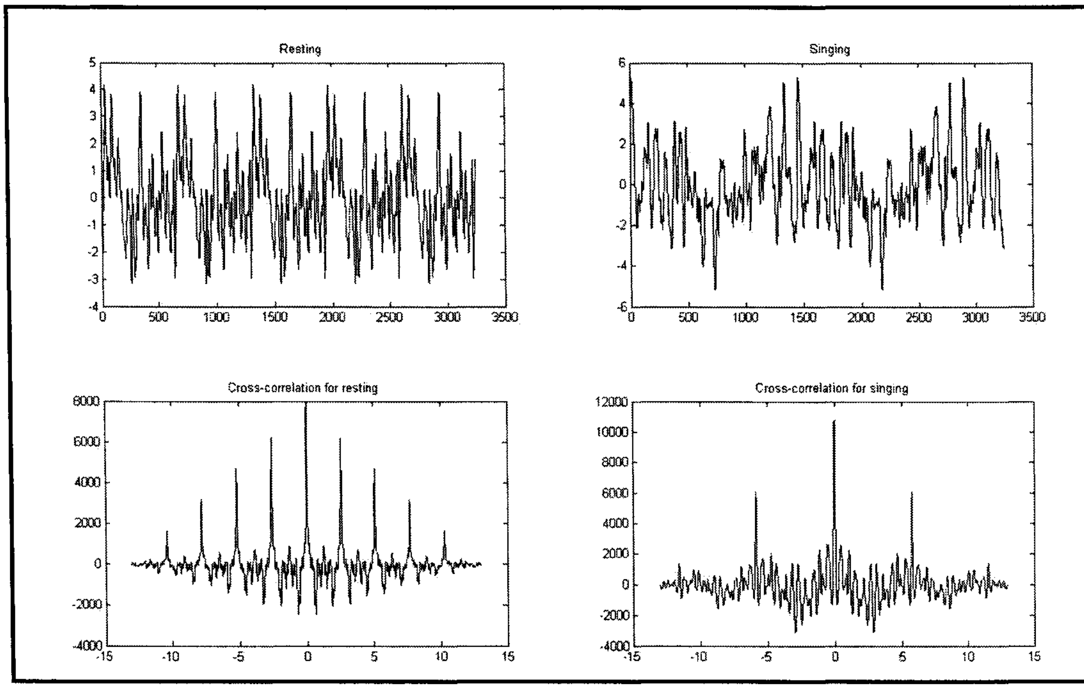
Figure 21. EMG amplitudes and frequencies for each participant. A) Minimum and maximum EMG amplitudes with standard deviations are shown for rest and singing conditions.


Resting
Singing
Cross-correlation for resting
Cross-correlation for singing
x 10^4
x 10^4

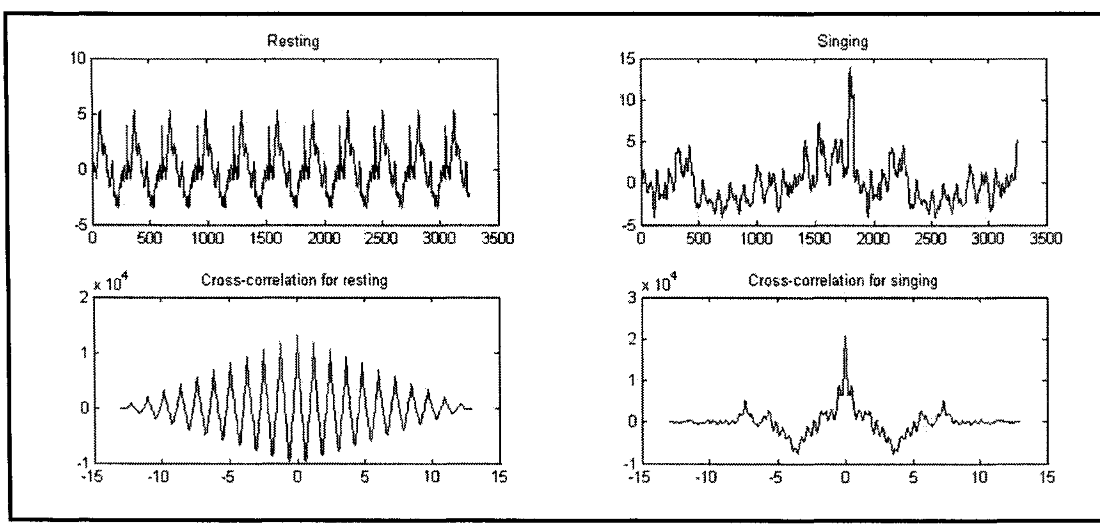
E1


Resting
Singing
Cross-correlation for resting
Cross-correlation for singing
x 10^4
x 10^4

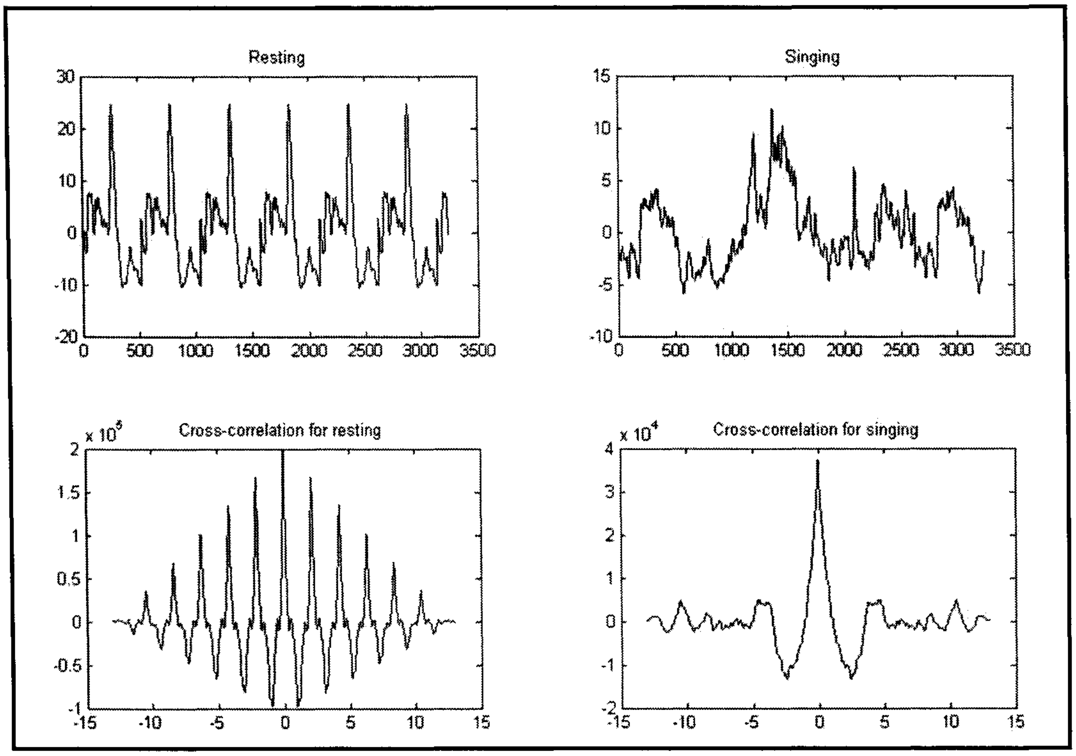
E4


Resting
Singing
Cross-correlation for resting
Cross-correlation for singing

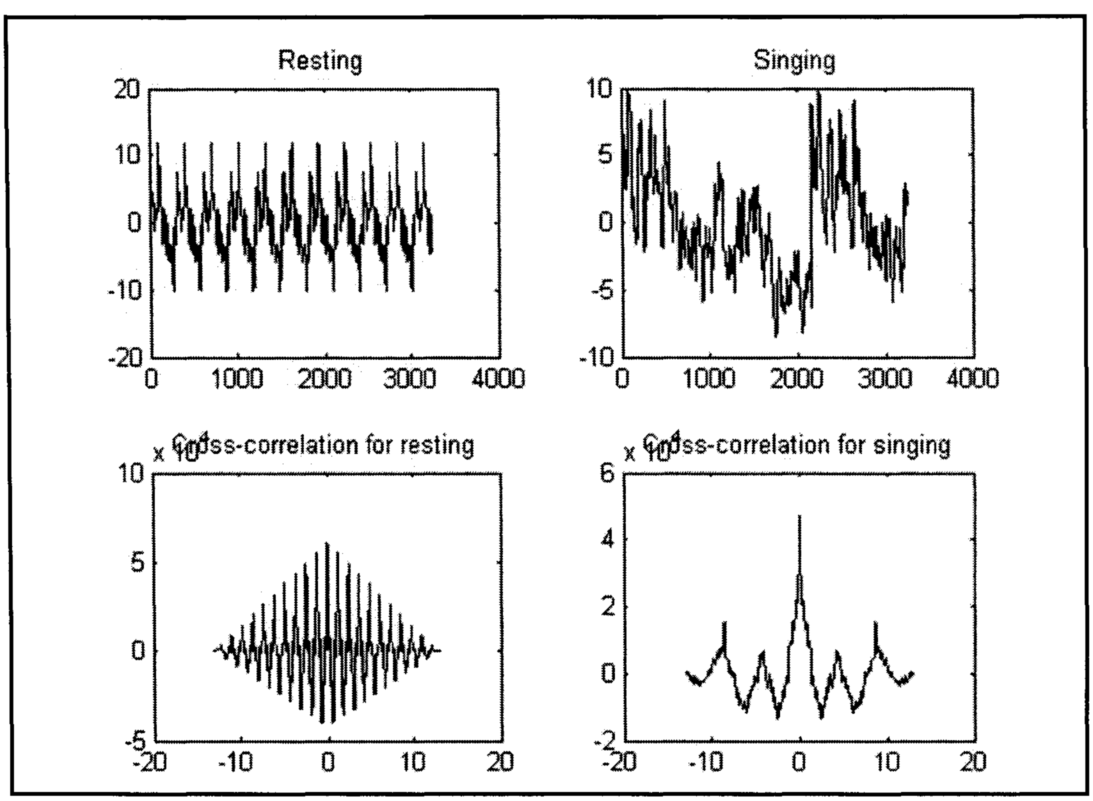
E5


Resting
Singing
Cross-correlation for resting
Cross-correlation for singing

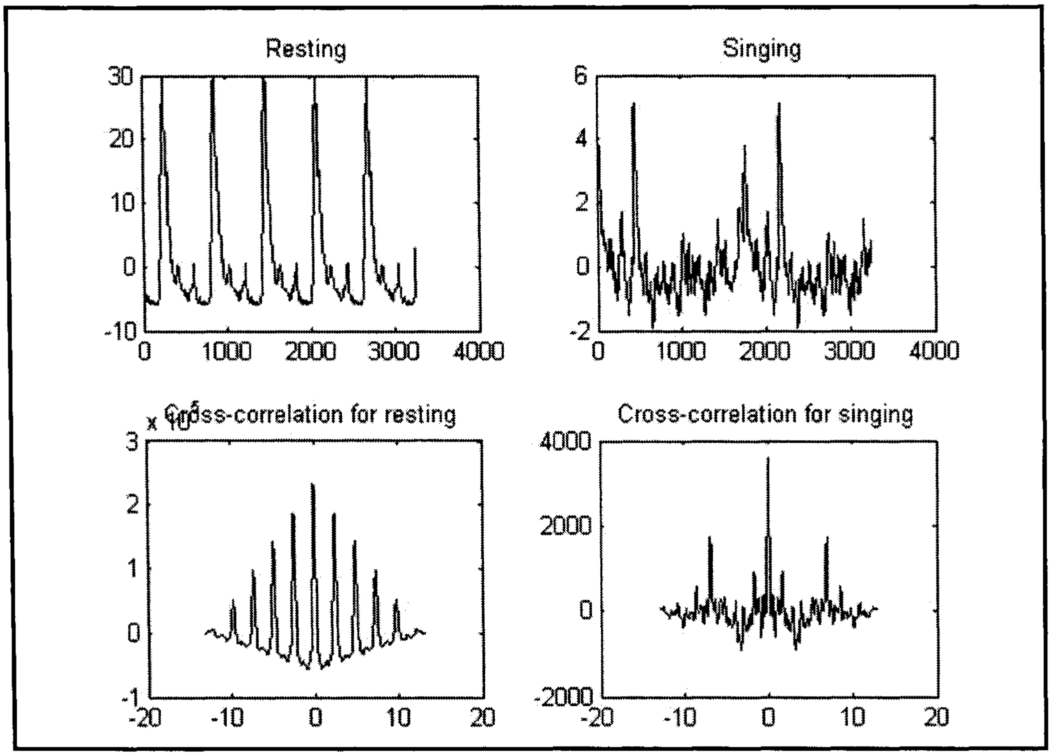
E8


Resting
Singing
Cross-correlation for resting
Cross-correlation for singing
x 10^5
x 10^4

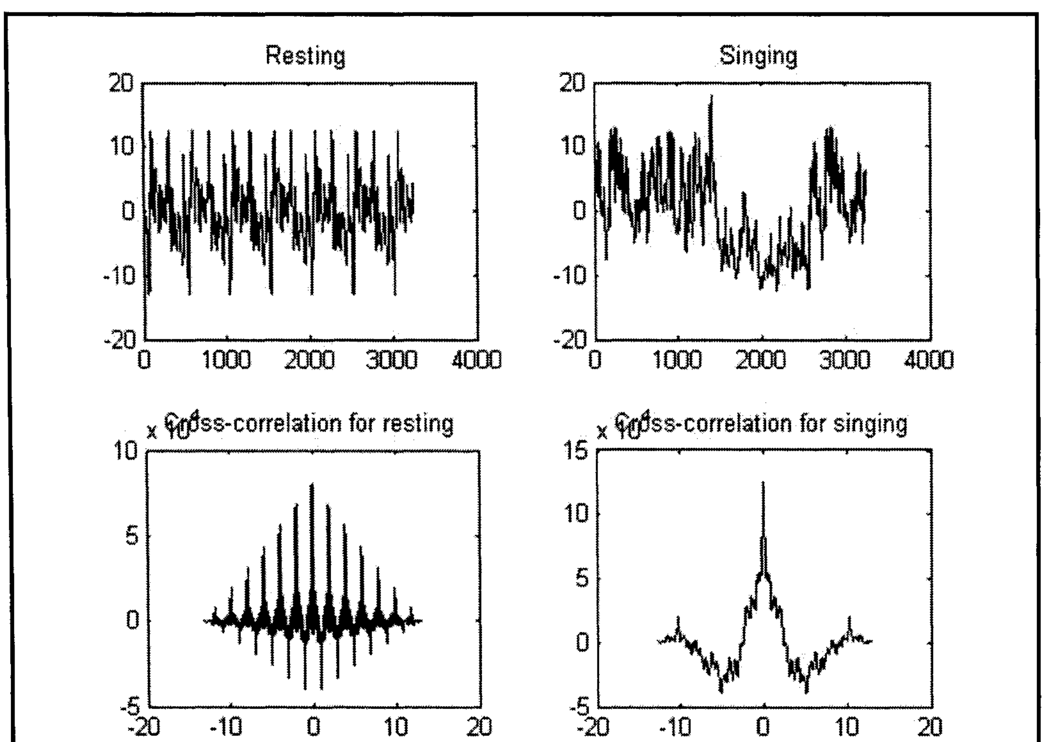
E9


Resting
Singing
Cross-correlation for resting
Cross-correlation for singing

E10



E12



E13

Figure 22. EMG frequencies and cross-correlations for each participant during rest and singing conditions.

APPENDIX J

BOXPLOTS COMPARING STATIC AND DYNAMIC GROUPS ON ADDITIONAL VARIABLES

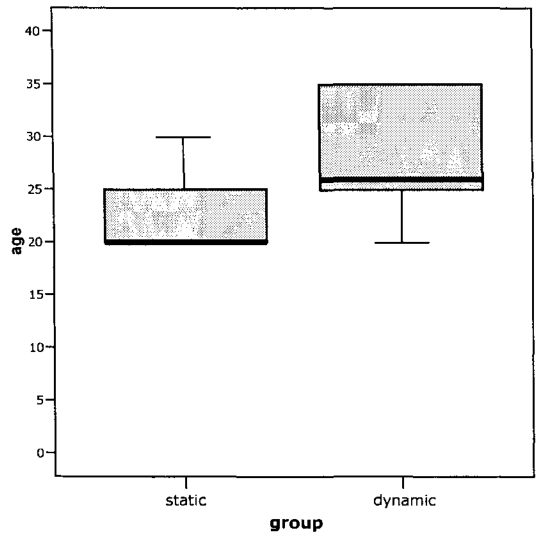


Figure 23. Boxplot comparing age for static and dynamic groups.

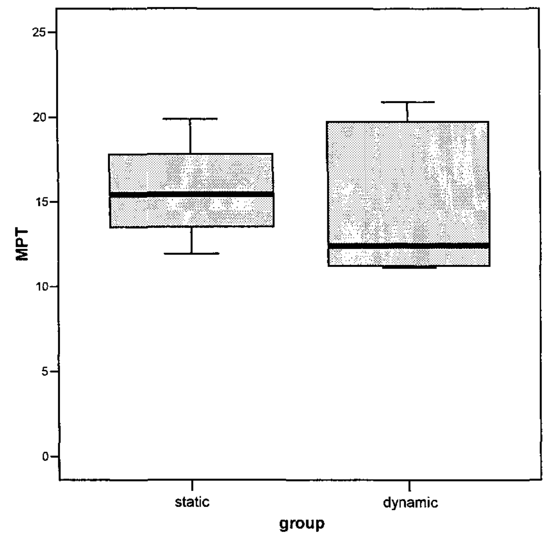


Figure 24. Boxplot comparing maximum phonation time for static and dynamic groups.

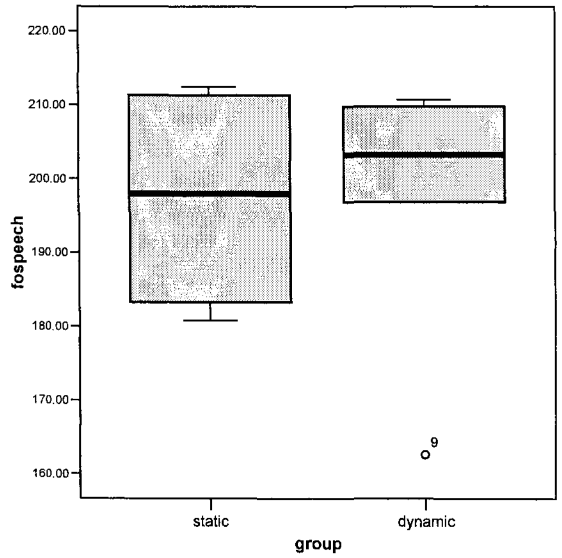


Figure 25. Boxplot comparing F_0 for speech for static and dynamic groups.

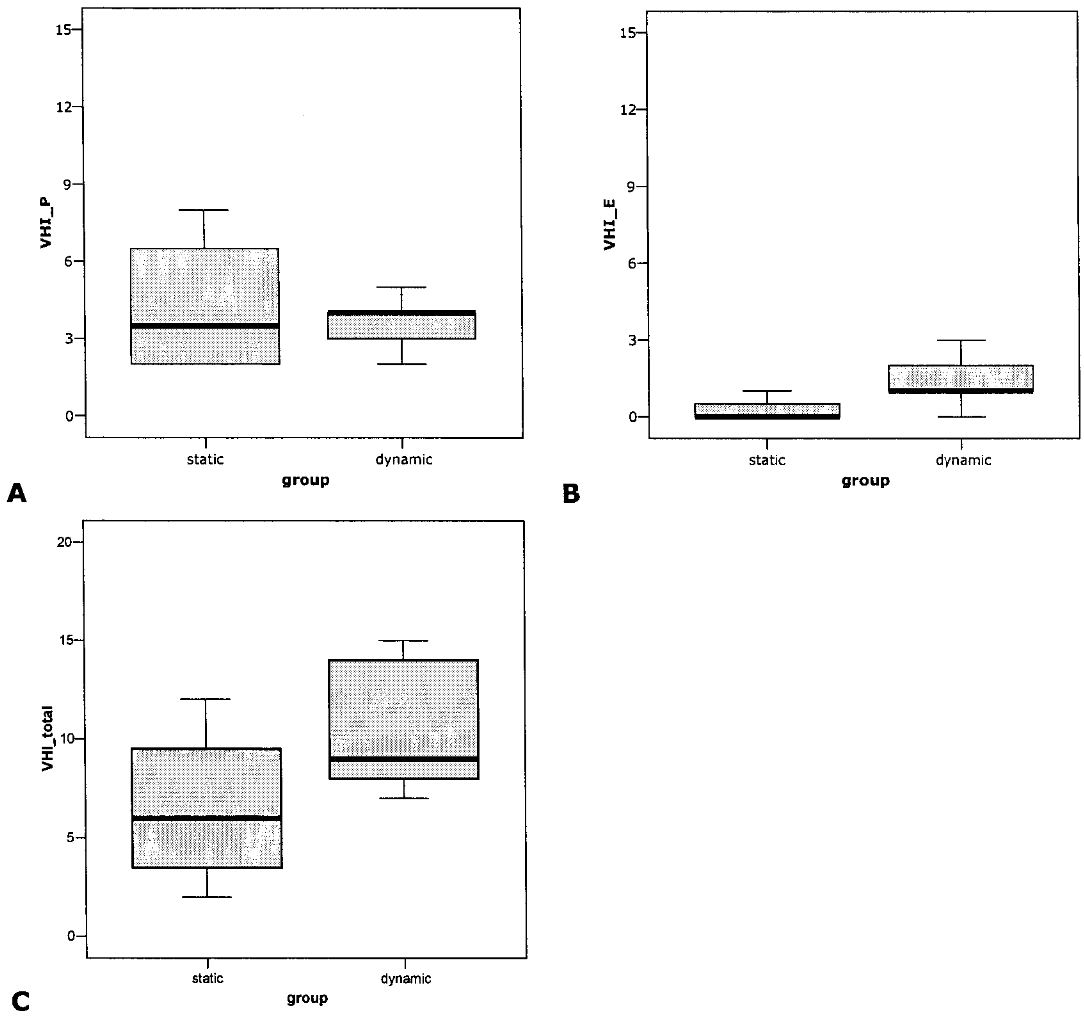


Figure 26. Boxplots comparing VHI scores on the Physical subscale (A), the Emotional subscale (B) and total score (C) for static and dynamic groups.

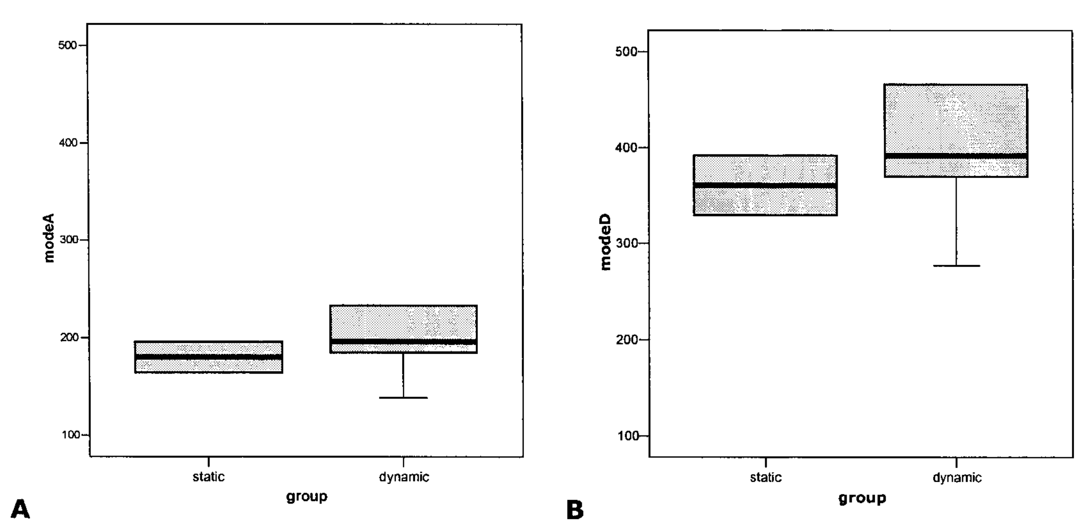


Figure 27. Boxplots comparing mode starting (A) and ending (B) pitches in production of scales for static and dynamic groups.

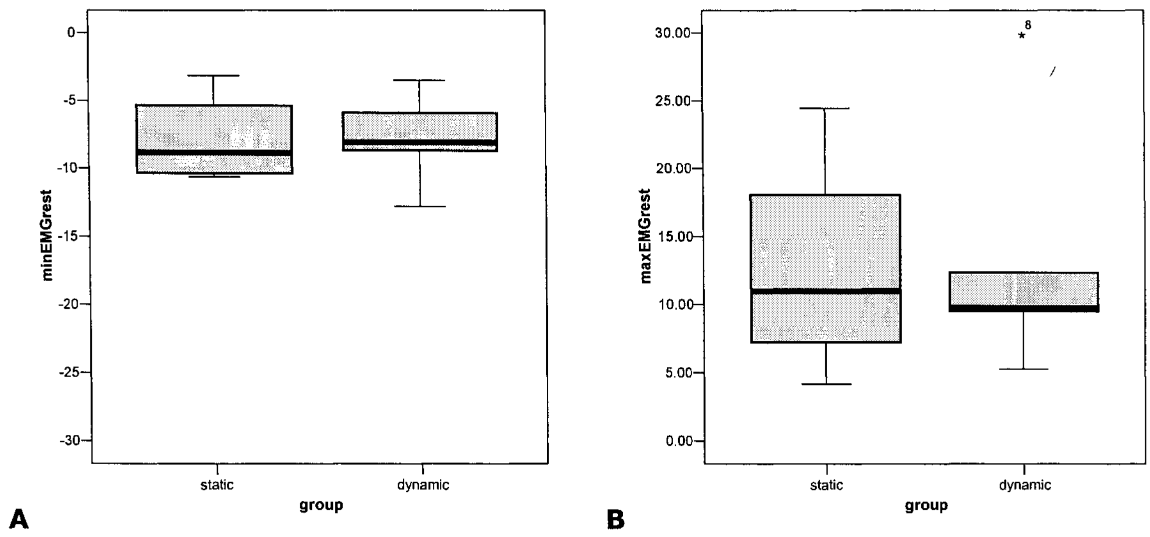


Figure 28. Boxplots comparing minimum EMG (A) and maximum EMG (B) amplitudes during rest condition for static and dynamic groups.

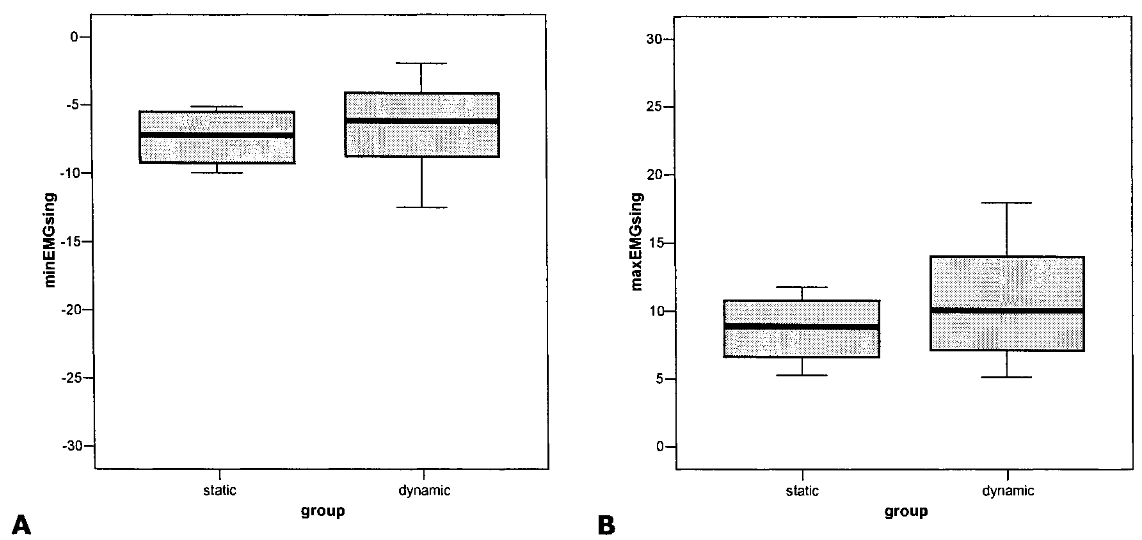


Figure 29. Boxplots comparing minimum EMG (A) and maximum EMG (B) amplitudes during singing condition for static and dynamic groups.

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