Laryngeal Muscle Activity and Vocal Fold Adduction During Chest, Chestmix, Headmix, and Head Registers in Females

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Summary: Hypothesis. Commercial singers produce chestmix register by maintaining or increasing adduction of the vocal processes (VPs) and by engaging the thyroarytenoid (TA) muscle to a greater degree than they would to produce head register.

Study Design. Prospective cohort study.

Methods. Simultaneous recordings of TA and cricothyroid (CT) muscle activity, videonasendoscopy, and audio were obtained from seven female singers during production of a variety of midrange pitches in chest, chestmix, headmix, and head registers. Fast Fourier transforms were performed to measure the energy in the fundamental frequency and in mid and upper frequency harmonics to determine if the productions that were judged as perceptually distinct registers also showed distinctive acoustic characteristics. Then, measures of TA and CT muscle activity and vocal fold adduction ratings were obtained to determine how these varied as a function of pitch and register.

Results. Spectral tilt increased as subjects shifted from chest to chestmix to headmix and finally into head register. For same pitch phonation, subjects increased TA muscle activity and vocal fold adduction as they shifted register from head to headmix to chestmix to chest, particularly during production of higher frequencies. CT activity appeared to be more related to pitch rather than register control.

Conclusion. Nonclassically trained singers were able to produce pitches at the high end of the midrange in chestmix register by increasing TA muscle activity and adduction of the VPs.

Key Words: Vocal registers–Chestmix–Headmix–Thyroarytenoid muscle–Cricothyroid muscle–EMG.

INTRODUCTION

Over the years, vocal registers and register terminology have been topics of much debate, ambiguity, and disagreement among singers, singing teachers, and voice scientists alike. An understanding of register control is fundamental to the study of singing. The term register is defined as a series of frequencies that are perceived to be of similar quality and produced in a similar physiologic manner.[1,2] Results of numerous acoustic, aerodynamic, and physiologic studies have gradually improved our understanding of three vocal registers; chest, falsetto, and glottal fry. However, among singers, additional registers have been identified, such as head, middle, and more recently, chestmix and headmix.

Middle voice has been defined by Miller[3] as the area of the female voice that lies between the primo and secundo passagios. He states that this area may also be referred to as "mixed" voice. Miller[3] further discusses middle voice in terms of "chest mixture" and "head mixture," stating that, for the female classical singer, chest mixture is the middle voice timbre most commonly encountered in the female lower middle voice and is characterized by limited head sensation. He describes head mixture as headier than chest mixture with increasing head sensation as the singer moves into her upper middle voice.

Although there is some argument among singing teachers and voice scientists as to the existence of these registers, the trained singer learns to transition from chest to falsetto and most singers and singing teachers agree that the transitional area is perceptually different from chest or falsetto, hence the terms "middle" and "mixed voice" have evolved in an attempt to describe this type of phonation. Although the distinguishing acoustic and physiologic factors have not been clearly identified for these registers, Table 1 provides generally accepted definitions for common register terminology. Many singers perceive the "middle" voice to possess perceptual and sensory characteristics of both chest and head. In addition, the perceptual quality of the transitional area often seems different for the female classical singer than for the female commercial singer; thus, the terms headmix and chestmix have recently come into use to differentiate type of "middle" voice. Register control is one of the variables that differentiate classical and commercial singers. In general, classical singers tend to transition to headmix and head voice at relatively lower pitches in their range, whereas commercial singers tend to produce the tones in the mid and upper portions of their range in chest or chestmix.

Perception of vocal register has been found to be strongly linked to the spectral tilt of the acoustic signal.[4,5] Keidar et al[4] reported that tones were perceived as produced in chest register when the spectral tilt of the signal was relatively shallow (12 dB/octave or less). Tones were perceived as produced in falsetto register when the spectral tilt was relatively steep (18 dB/octave or greater). Tones produced with spectral tilts

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TABLE 1.
Register Terminology

Term	Description
Chest	Also referred to as "modal." Characterized perceptually by a rich timbre and acoustically by a shallow spectral tilt.
Belt	A style of singing. Not a register. Belt is high-pitched chest voice, that is, chest voice carried above first passagio (register transition), with no mixing of the chest and head registers.
Mixed	Perceptually judged as having some characteristics of both chest and head registers. Transition between the chest and head registers.
Middle	Middle register is another term for mixed register.
Chestmix	Perceptual and acoustic characteristics are more similar to chest voice than to head register.
Headmix	Perceptual and acoustic characteristics are more similar to head voice than to chest register.
Legit	A style of singing. Not a register. Characterized by head dominant mix produced with a speech-like formants (ie, vocal tract is not modified as in classical singing).
Head	Characterized perceptually by a bell-like timbre and acoustically by a strong first formant, less high frequency energy in the spectrum, and a steep spectral tilt.

between 12 and 18 dB/octave were difficult to consistently identify as either chest or falsetto. It is reasonable to speculate that these tones were produced in what would be identified as a mixed register. Many studies have shown that chest, as well as many commercial styles of singing, tend to show greater energy in the mid and upper frequency harmonics than falsetto or classical styles of singing; and although studies comparing the acoustics of commercial singing styles with classical styles did not identify vocal register, the results are surprisingly consistent; commercial styles tend to show acoustic characteristics that are more similar to chest phonation than to falsetto.[6–15]

Although there is a fairly substantial amount of acoustic data for the chest and falsetto registers, data for middle voice are sparse. There is limited evidence that middle voice shows characteristics that distinguish it from chest.[16] Large[16] examined the narrow band spectrums of five trained female singers during same pitch phonation in chest and middle voice. Middle voice had greater energy in the fundamental than chest but less energy in the high frequency harmonics than chest.

Results from electromyographic (EMG) studies have shown that for trained male classical singers and male nonsingers, all intrinsic laryngeal muscle activity is generally greater for chest than falsetto during same pitch phonation.[17–20] Likewise, Estill et al[10] found that for one male classical singer, thyroarytenoid (TA) muscle activity was greater during belt productions than same pitch productions produced in an operatic style and in falsetto.

One study has investigated laryngeal muscle activity in female singers during the production of middle voice. Hirano[20] measured TA and cricothyroid (CT) muscle activity during production of same pitch phonation produced in chest, middle, and head in one trained female classical singer. He found TA muscle activity was greater for middle voice than for head voice but less than for chest. He also reported little change in CT muscle activity by register.

Numerous studies have examined vocal fold adduction patterns indirectly via electroglottography (EGG), photoglottography, and inverse filtering and have reported greater vocal fold adduction for chest and for commercial singing styles as compared with falsetto and classical singing styles.[10,12–15,21–23] These studies reported greater closed quotients, longer closed phases, smaller peak flow amplitudes, shorter open quotients, increased skewing quotients, and longer opening times for chest and commercial singing styles as compared with falsetto and classical singing styles.

More recently, Herbst et al[24] reported four distinct glottal configurations for four different voice qualities in one classically trained baritone. They examined glottal configuration, vocal fold vibratory patterns, and closed quotients via videostroboscopy, videokymography, and EGG during production of naïve falsetto, countertenor falsetto, lyrical chest, and full chest produced on D4. Results from the videostroboscopic study showed four distinct glottal configurations and different vibratory features: (1) during naïve falsetto, a slightly open posterior glottis and vibration of the vocal processes (VPs); (2) during countertenor falsetto, adducted posterior glottis and intermittent vibration of the VPs; (3) during lyrical chest, a barely closed posterior glottis and VPs involved in vibration; and (4) during full chest, adducted posterior glottis and no VPs vibration. EGG and videokymography results showed increasing vocal fold contact and increased closed quotients as the subject changed from countertenor falsetto to lyrical chest to full chest.

Only one study has investigated the acoustic, aerodynamic, and vocal fold adduction characteristics of mix as compared with belt (chest) and opera (head). Sundberg et al[11] examined narrow band spectrograms, calculated glottal permittance (the ratio of peak flow amplitude and subglottal pressure), and observed changes in vocal fold adduction during nasendoscopy in one trained female singer during the production of belt (chest), mix, and opera (head). Mixed voice showed the most energy in the mid and upper harmonics, then belt. Opera showed the least. Vocal fold adduction was complete for belt, showed a posterior gap for mix, and was incomplete for opera. Glottal permittance was greater for opera than for mix or belt, which were nearly the same. Subglottal pressure was greatest for belt and the same for mix and opera.

Current theories of register control point to registration as a primarily laryngeal event, dependent on laryngeal muscle activity, degree of vocal fold adduction, and glottal shape.[4,5,23,25,26] However, many of the components of these theories remain untested in regards to registers other than chest and falsetto.

The ability to maintain chest or chestmix in the upper frequency range (G4–F5) has become a highly sought after skill for the female commercial singer. However, although investigation of belt voice has increased, little research has been conducted to further the understanding of the production of "mixed" type registers. Based on the findings from the Sundberg et al[11] study of belt, mix, and opera and data from a number of studies that have examined the acoustic and EGG and flow glottogram waveform characteristics of various commercial singing styles, the production of chestmix through the upper-middle and upper pitches may involve increased vocal fold adduction and increased TA activity. Titze[27] has speculated that the trained singer may separate the VPs as pitch is increased in chest to offset increased TA activity and then gradually decrease TA while CT activity increases, thus ensuring a smooth register transition from chest to head. However, the actual mechanisms by which female commercial singers maintain chest or chestmix as they traverse the upper middle and upper pitches are not currently known.

Although there is evidence that register control is dependent on adjustments made at the level of the larynx, there has not been a systematic study of these adjustments across different registers and singing styles. In addition, there are a number of problems with the current information available on commercial voice styles. First, only one study has attempted to compare high-pitched chest (belt) and mix productions, the two primary registers used in commercial singing, to head or opera voice. Other studies have compared different commercial voice styles with classical voice styles but without regard to or identification of register. Second, most studies investigating commercial singing in women have either been single subject or small group studies, making the findings difficult to generalize. Finally, with exception of recent studies specifically investigating belt voice, most studies investigating female commercial singers have, in general, examined phonation over a rather narrow and low pitch range. For female commercial singers, the pitch range of interest is approximately F4–E5, where chest and chestmix are used instead of headmix or head.

The existing laryngeal muscle activity data for females during the production of chest and head registers comes from only three trained female classical singers and the data for middle voice from only one subject.[17,20] Absent from the literature is empirical investigation of laryngeal muscle activity in commercial female singers during production of all vocal registers. Thus, little is known about laryngeal muscle activity during the production of the "mixed" or "middle" registers.

To understand how female commercial singers control register and pitch, especially during high-pitched chest or chestmix phonation, a systematic study must be conducted in which TA muscle activity and vocal fold adduction are measured during a variety of singing tasks produced in the pitch range of interest (F4–E5). The results from such research may provide new information regarding register and pitch control that is important to the fields of voice science, voice therapy, and vocal pedagogy. Little is known about the mechanisms involved in the production of "mixed" registers, such as chestmix and headmix or about how pitch is controlled within these registers. Furthermore, an understanding of how chestmix is produced will help singing teachers better instruct students who wish to produce this register and help us to understand how it may be produced in a healthy manner.

The purpose of this study is to test the hypothesis that female commercial singers are able to maintain chestmix while producing pitches in the upper-mid and upper part of their frequency range by maintaining or increasing vocal fold adduction and by engaging the TA muscle to a greater extent than they would to produce the headmix and head registers.

METHODS

Subjects

Seven female singers (21–52 years old) participated in the study. Subject characteristics are listed in Table 2. Of the seven singers, two were professional or semiprofessional nonclassical singers with 10–12 years of professional voice training. Two were both classical and nonclassical singers with 1–2 years of classical training only. One was a nonclassical singer with 5 years of private classical training primarily as a child and two were essentially untrained nonclassical singers.

The subjects were interviewed to ensure that they had no history of voice or speech disorders, bleeding problems, allergy to subcutaneous anesthetic agents, or history of smoking. All subjects were cautioned against the use of aspirin or Coumadin (Bristol-Myers Squibb Company, New York, NY) within 14 days before the experiment day. A head and neck screening exam was performed on each subject by the participating laryngologist on the day of the experiment to ensure that the laryngeal anatomy and gross movement of the vocal folds were within normal limits.

Subjects were screened by a professional singing teacher to verify the subjects' ability to produce same pitched phonation in at least three of the following vocal registers: chest, chestmix, and headmix or head register. All subjects could produce or be coached to produce at least three of the target registers over a minimum of 3–4 semitones.

Procedure

Simultaneous recordings of TA and CT muscle activity, videonasendoscopy, and audio were obtained from the subjects during phonation.

Laryngeal EMG. The subjects were seated upright in a comfortable chair. A reference electrode was placed on the forehead of the subject. A small amount (0.5 cc) of 2% lidocaine with 1:100 000 epinephrine was injected just below the surface of the skin overlaying the CT ligament before electrode insertion. Stainless steel bipolar hooked-wire electrodes (0.0003 in) were then inserted percutaneously through a 25-gauge needle bilaterally into the TA and CT muscles. All electrode insertions were performed by an otolaryngologist with extensive experience with laryngeal EMG.

The bipolar hooked-wire electrodes and ground electrode were connected to a preamplifier (B466, Bioengineering, The University of Iowa, Iowa City, IA). Output from the preamplifier was directed to a bioamp speech physiology system

TABLE 2.
Subject Characteristics and Vocal Registers Produced by Each Subject During Sustained Phonation Tasks

Subject	Age	Years of Training	Type of Training	Professional Level	Musical Style	Chest	Chestmix	Headmix	Head
S1	47	12 y	Nonclassical	Professional singer, singing teacher	Jazz and pop; solo	√	√		√
S2	36	10 y	Nonclassical	Semiprofessional	Musical theater and pop; solo and theater choir	√	√		√
S3	21	<1 y	Nonclassical	Semiprofessional and avocational	Pop and R&B; solo	√	√		√
S4	52	2 y	Classical	Semiprofessional	Classical, folk, and choir; solo and choir			√	√
S5	26	1–2 y	Classical	Avocational	Christian pop and country; church choir some solo			√	√
S6	26	5 y; age 6–11 y	Classical	Avocational	Pop; solo and church choir	√	√		√
S7	35	None	None	Semiprofessional and avocational	Barbershop and church choir	√	√		√

(Bioengineering, The University of Iowa, Iowa City, IA) and high pass filtered at 300 Hz. EMG signal output from the bioamp was then low pass filtered at 5 kHz via a Dual High/Low Pass Filter (Wavetek 432; Rockland, MA). EMG signals were then directed to an analog to digital converter (DI-205; Dataq Instruments, Akron, OH), which was connected to a portable two-channel parallel port I/O Module (DI-720; Dataq Instruments, Akron, OH) thus allowing signals to be recorded onto a laptop computer (Dell Latitude, Dell, Austin, TX) via waveform acquisition software (*Windaq Pro+ data acquisition software*, Dataq Instruments, Akron, OH). Sampling rate for the EMG data acquisition was 10 000 Hz/channel.

Simultaneous audio recordings were recorded directly into the Windaq data acquisition program via laptop computer (Dell Latitude) by connecting a microphone directly into the analog to digital converter (DI-205; Dataq Instruments, Akron, OH). Placement of the hooked-wire electrodes into the TA muscle was judged correct if there was EMG activity associated with the verification tasks and if the CT membrane was pierced during insertion.

Nasendoscopy. After electrode placement, a topical anesthetic (4% lidocaine with phenyl epinephrine) was sprayed into one of the subject's nares. The nasendoscope was then inserted and visualization of the vocal folds was obtained before data recording began. The nasendoscopic procedure was recorded onto video home system (VHS) tape via a video cassette recording (VCR) system, which included audio recording via a remote microphone system. Two additional audio signals were also recorded, one directly into the computer and one into a digital audio tape (DAT) recorder.

The nasendoscopic data was obtained with a Pentax flexible nasendoscope (Pentax VLN 1330, Pentax, Montvale, NJ) and a halogen light source (Pentax EPM 1000, Montvale, NJ). Nasendoscopic images were recorded with a VCR system (Panasonic AG-1730, Proline, HiFi MT Broadcast Stereo Multiplex VCR, Osaka, Japan) onto super VHS tape, and audio recordings were made for the video via a remote microphone system (Sennheiser EW 100, Sennheiser, Wedemark, Germany). The VHS tapes were digitized at 48 000 samples/s with video digitizing software (*Final Cut Pro*, 2003, Apple, Cupertino, CA) and saved to DVD for further editing. Video stills of vocal fold adduction were made with video editing software (Final Cut Pro, 2003, Apple, Cupertino, CA).

Audio signal. Audio signals were recorded via DAT recorder (Sony PCM-M1, Tokyo, Japan) at a sampling rate of 41 100 samples/s. Microphones used to acquire the audio signals included a head mounted condenser microphone (AKG, C42, Vienna, Austria), and three types of condenser microphones (Sony Electret ECM-MS907 Condenser Microphone, Tokyo, Japan; Radioshack Omni-Directional Electret 33-3013 Condenser Lapel Microphone, Fort Worth, TX; Sony Dynamic Omni-Directional F-VS3, Tokyo, Japan). Audio recordings were then digitized with audio editing software (*Sonic Sound Forge*, 2005, Sony, Tokyo, Japan) at a sampling rate of 44 100 samples/s and edited into sample tokens for perceptual rating.

Tasks

After electrode placement in the target muscle, verification tasks were performed to confirm electrode placement. To confirm CT placement, subjects were asked to produce (1) a sustained high pitch; (2) an ascending pitch glide; and (3) a chin press. Placement of the hooked-wire electrodes into the CT muscle was judged correctly if there was increased EMG activity associated with high-frequency phonation, an absence of EMG activity during a chin press, and the CT membrane was not penetrated during insertion. To confirm TA muscle placement, subjects were asked to (1) produce hard glottal attacks; (2) perform a valsalva maneuver; (3) sustain phonation at a comfortable pitch; and (4) swallow.

To obtain levels of maximum muscle activity, the subjects were asked to perform five tasks that are commonly used to elicit maximum TA and CT muscle activity; a swallow, a valsalva maneuver, a hard adduction, a loud high-pitched phonation, and a cough. Subjects produced each task three times both pre- and postexperiment. The subjects were then asked to produce chest voice, chestmix, and headmix or head voice during sustained phonation on /i/ or /ne/ at 3–5 frequencies (Eb4–F4, Eb4–G4, E4–Ab4, or F4–A4 or Bb4, depending on voice type), in the subject's frequency range of interest. Sustained phonation tasks were repeated 3–5 times per frequency per register. Vocal intensity was not controlled so that subjects could produce the target registers naturally.

Measurement

Perceptual judgment of register.

To determine which registers were successfully elicited from the subjects, all the singing tokens were perceptually rated as chest, chestmix, headmix, or head voice by two trained judges. The judges were two professional commercial singing teachers with 15 and 8 years of experience, respectively. Each judge was provided with a compact disc (CD) with recorded samples of singing produced in the chest, chestmix, headmix, and head registers by professional singers. The CD was compiled by the primary investigator and consisted of song phrase segments from well-known female vocalists that exemplified (1) high-frequency chest production (belting); (2) chestmix; (3) headmix; or (4) head voice. A list of the phrases or portions of the phrase that were produced as chest, chestmix, or headmix or head was provided to each judge along with the CD. Appendix shows the list of artists, songs, and song phrases used on the training CD. The judges were asked to listen to the CD before rating the subjects' singing tokens and were encouraged to refer to the CD for recalibration as often as was needed. The audio recordings of the subjects' singing tokens were randomized for each subject and presented to the judges for categorization without the accompanying video recordings.

Laryngeal EMG.

Measurements of TA and CT muscle activity were obtained for all singing tasks using Windaq signal processing and analysis software. First, the TA and CT EMG signals were inspected visually and aurally for artifact, and areas of maximum CT and TA muscle activity were identified and the maximum root mean square values during a 20-millisecond window were recorded for each muscle. Second, the EMG signals were rectified and then smoothed by obtaining a moving average from the digitized signal (with a 50-millisecond window using a smoothing factor of 250). Third, mean TA and CT muscle activity for each sustained phonation singing token was obtained by measuring mean TA and CT muscle activity at the middle one third or middle two fourths of the token to avoid muscle activity onset and offset bursts. Sample segments measured were from 300 to 700 milliseconds in length.

Measures of maximum TA and CT muscle activity were used to calculate the percent of maximum activity for the mean TA and CT muscle activity obtained for each singing task. Data normalization allowed for comparison of TA and CT muscle activity as a function of pitch and register both within and across subjects.

Nasendoscopy.

Vocal fold adduction, that is, size of the vocal processes gap (VPG), was rated for degree of closure during sustained phonation on a scale of -5 (maximally abducted) to +5 (maximally adducted). The vocal fold adduction and abduction rating scale values were relative to the maximum vocal fold adduction and abduction observed for each subject. Video stills of vocal fold adduction during each token of sustained phonation were cut from the digitized videonasendoscopic data for each subject, numbered, randomized, saved to a CD, and presented to the judges for rating. The judges were provided still photos of the subjects' maximally adducted (+5) and abducted (-5) vocal fold closures as a reference. The judges' ratings were then normalized on a scale of 1–5 with 1 equaling least abducted and 5 most adducted.

Audio signals.

Fast Fourier transforms (FFTs) were performed for all audio samples of sustained phonation to determine the amplitude of harmonics present with a software analysis program (*Windaq Pro+ data analysis software*). This was done by calculating the first 20 harmonics for each frequency and then using the cursor to locate the harmonics within the FFT spectrum. Peak frequencies were accepted as harmonics if the peak frequency was the harmonic or it contained the harmonic within 20 Hz of the peak frequency. In addition, the mean amplitudes of the harmonics in the singer's formant and speaker's formant clusters were measured. In this study, the singer's and speaker's formants are defined as a clustering of formants for which the amplitudes are noticeably increased in comparison with the surrounding harmonics, resulting in fairly prominent peaks of energy in the 2–3 kHz (singer's formant) and 3.5–5 kHz (speaker's formant) regions. Data were then compared across registers.

Reliability

To measure intrajudge reliability for the perceptual rating task, 20% of the singing samples from each subject were reevaluated. The audio recordings of the singing tokens to be reevaluated were randomized and presented without the accompanying video recordings. To measure intra- and interjudge reliability for the vocal fold adduction rating task, 10% of the vocal fold adduction video clips from each subject were reevaluated. Still photographs of vocal fold adduction were randomized and

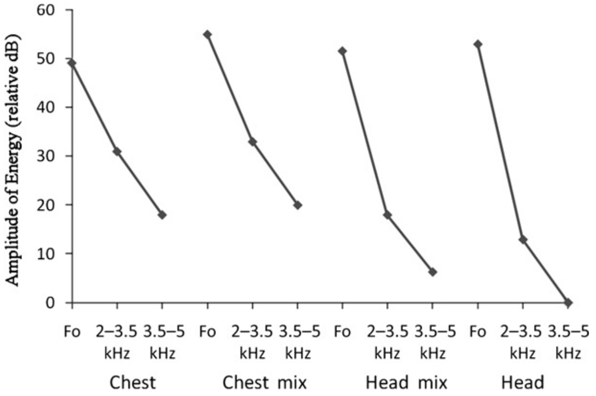

FIGURE 1. Mean energy in decibels for the fundamental frequency and singer's and speaker's formant clusters for all subjects during chest, chestmix, headmix, and head.

presented without the accompanying audio recordings. Cohen's kappa coefficient tests were performed to measure both inter- and intrajudge reliability.

RESULTS

Perceptual judgment

Not all subjects produced the target vocal registers at every pitch during the sustained phonation tasks. Table 2 shows the registers each subject reliably produced as perceptually confirmed by the two expert judges. Data analysis were based on what the subjects actually produced, as opposed to what they were requested to produce. Four hundred eighty-nine tokens were obtained from the seven subjects (averaged 69 per subject, range of 56–79). Judges agreed in terms of identification of the register on 335 of the 489 tokens. The tokens for which interjudge agreement was not obtained were not included in the data analysis. For the 335 tokens analyzed for this study, intrajudge reliability was assessed by having each judge reevaluate 20% of the tokens for each subject. Intrajudge reliability was measured using Cohen's kappa coefficient, which takes into account the agreement occurring by chance. The interpretations of the kappa values are: <0.00 = poor; 0.00–0.20 = slight agreement; 0.21–0.40 = fair agreement; 0.41–0.60 = moderate agreement; 0.61–0.80 = substantial agreement; and 0.81–1.0 = almost perfect agreement.[26] Intrajudge reliability yielded a kappa score of 0.75 for the first judge and 0.70 for the second judge, indicating substantial agreement.

Acoustic analysis

Acoustic analysis using FFTs showed that tokens that were perceptually judged as produced in distinctly different registers (chest, chestmix, headmix, and head registers) demonstrated distinctly different acoustic characteristics. Figure 1 shows the average energy of the partials at three points in the spectrum, the fundamental frequency (F_0), the midfrequency harmonics in the area of the singer's formant cluster (2–3 KHz), and the high-frequency harmonics in the area of the speaker's formant cluster (3.5–5 kHz) for chest, chestmix, headmix, and head registers. Table 3 provides the group mean (and standard deviation) values for energy in the F_0 and singer's formant and speaker's formant clusters for each register.

Tokens judged to be produced in chest and head registers were produced with different spectral characteristics, consistent with results of previous studies. As shown in Figure 1 (and Table 3), pitches produced in head register had more energy in the F_0 (not statistically significant) and less energy in the high-frequency partial (statistically significant at <0.01), resulting in a steeper spectral tilt in comparison with chest register productions. Pitches produced in chestmix were similar to those produced in chest but with a stronger F_0 (statistically significant at 0.01). Pitches produced in headmix were similar to those produced in head but with more energy in the high-frequency partials (statistically significant at <0.01).

Laryngeal EMG

TA muscle activity. Figure 2 shows TA muscle activity for each subject during production of multiple pitches in various registers. Verifiable TA insertions were obtained for all seven subjects. The number of data points varies across graphs. This reflects the variable degree to which subjects were able to produce the midrange pitches in multiple registers. Some subjects were able to produce a wide range of pitches in multiple registers (eg, S1 produced seven pitches in three registers); others produced a more restricted range of pitches (eg, S7 produced three pitches in three registers).

TABLE 3.
Group Means and Standard Deviations for Energy in the Fundamental Frequency and Singer's Formant and Speaker's Formant Clusters

Register	Fundamental Frequency	Singer's Formant	Speaker's Formant	Voice Process Gap
Chest	49 (4)[*]	31 (6)[†,‡]	18 (3)[†,‡]	4.00 (0.85)[†,‡]
Chestmix	55 (6)[*]	33 (6)[§,‖]	20 (8)[§,‖]	3.75 (0.60)[‖]
Headmix	52 (11)	18 (10)[‡,‖,¶]	6 (3)[‡,‖,¶]	2.20 (0.50)[‖]
Head	53 (7)	6 (3)[†,§,¶]	0 (5)[†,§,¶]	2.00 (0.70)[†,‡]

[*] Significant difference between chest and chestmix.
[†] Significant difference between chest and head.
[‡] Significant difference between chest and headmix.
[§] Significant difference between chestmix and head.
[‖] Significant difference between chestmix and headmix.
[¶] Significant difference between headmix and head.

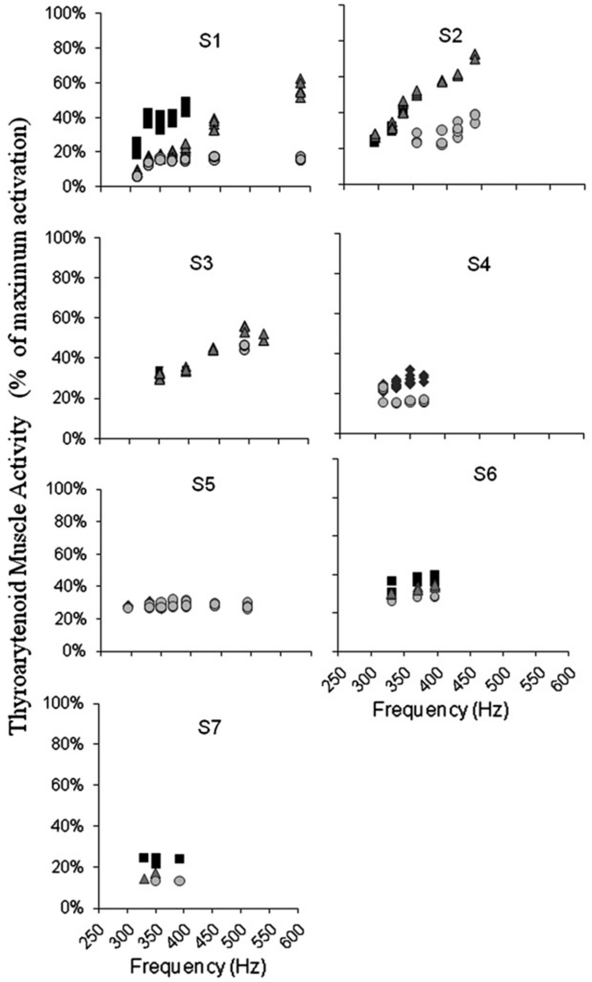

FIGURE 2. Thyroarytenoid muscle activity by register and frequency for each subject. Squares = chest, triangles = chestmix, diamonds = headmix, and circles = head.

When producing the same pitch in different registers, subjects maintained or increased TA muscle activity. At low pitches, subjects maintained TA muscle activity or increased it slightly as they shifted to a heavier register. At higher pitches, subjects were more likely to substantially increase TA muscle activity as they shifted to a heavier register.

The magnitude of TA muscle activity ranged from 5% to 72% of maximum activation. The lowest levels of activation were generally seen from production of lower pitches in head register and the greatest levels during production of higher pitches in heavier register. In lower frequencies, 294–350 Hz (D4–F4), TA activity was sometimes similar for chest and chestmix, head and chestmix, or headmix and head, depending on the subject. In some cases, the difference in TA activity across registers was small, but very consistent, as seen for S6. In other cases, differences were greater, as seen for S1 and S2. S1 showed increases in TA activity for chest as compared with head ranging from 10–20% greater at the lower frequencies to 20–25% greater at higher frequencies. Both S1 and S2 showed increases in TA activity for chestmix as compared with head ranging from 0–25% at the lower frequencies to 15–40% greater at the highest frequencies.

When increasing pitch within the same register, some subjects increased TA activity (eg, S1, S2, and S3). Other subjects maintained TA activity as pitch increased within a given register (eg, S5). There was a tendency for subjects (5 of 7) to show increased TA activity with frequency in chest and chestmix but little or variable change in activity with frequency in head and headmix.

Figure 3 shows the mean TA activity during sustained phonation as a function of register and frequency for the subjects as a group. Several observations were made regarding change in TA activation during same pitch phonation in different registers. At the lowest pitch (D4, 294 Hz), TA muscle activity did not change as register was altered. For the next five pitches (Eb4–G4, 311–392 Hz), small (5–10%) increases in TA activity are seen as the subjects moved from the lighter registers to the heavier registers. At the higher pitches (Ab4–D5, 411–585 Hz), a larger (20–30%) increase in TA activity was used to shift from head register to chestmix.

Within a register, as subjects increased pitch, TA muscle activity usually remained steady or increased slightly. The exception is seen during pitches produced in chestmix register. In this register, TA muscle activity was substantially increased during production of higher pitches in comparison with lower pitches. For two subjects (S1, S2), TA activity appeared to increase with pitch in chestmix register to a greater extent in the area of the primo passagio (F4–A4).

CT muscle activity. Verifiable CT muscle insertions were obtained for three subjects (S1, S4, and S5). Figure 4 shows the mean CT muscle activity during sustained phonation as a function of register and frequency for subjects S1, S4, and S5.

Within a given register, CT muscle activity tended to increase with pitch in subjects who were able to produce a wide range of pitches (ie, S1 and S5). Subject S4 did not alter CT muscle activity substantially; however, she also did not provide a wide range of pitches.

When producing the same pitch in different registers, subject performance was variable. Subjects S1 and S4 maintained or increased CT muscle activity, whereas S5 decreased CT muscle activity.

Muscle activation plots

Muscle activation plots (MAPs), introduced by Titze,[27] show percent of maximum CT activity as a function of percent of

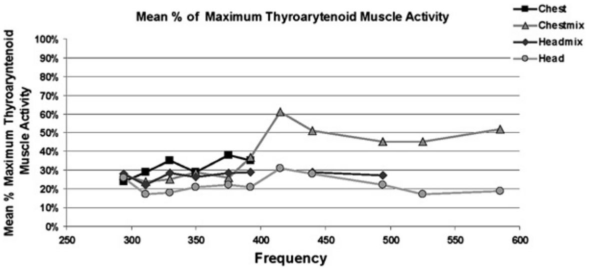

FIGURE 3. Mean percent of maximum thyroarytenoid muscle activity during chest, chestmix, headmix, and head by frequency for all subjects.

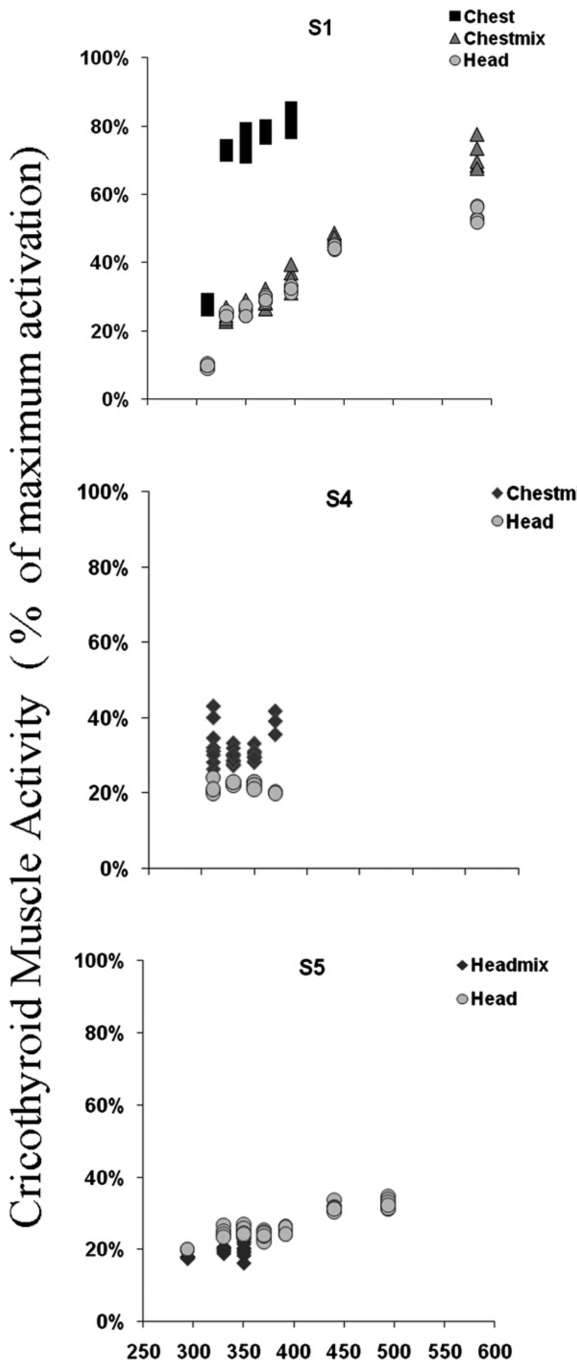

FIGURE 4. Percent of maximum cricothyroid muscle activity by register and frequency for subjects S1, S4, and S5.

maximum TA activity. According the Titze,[27] the MAPs can be divided into four quadrants; the speech quadrant (the lower left quarter), the falsetto quadrant (upper left quarter), the chest quadrant (upper right quarter), and the pressed quadrant (lower right quarter).

MAPs were constructed for two subjects for whom both CT and TA EMG data were obtained (see Figure 5). Both subjects produced a wide range of pitches (see Figure 2). Subject S1 produced pitches in a wider variety of registers than subject S5.

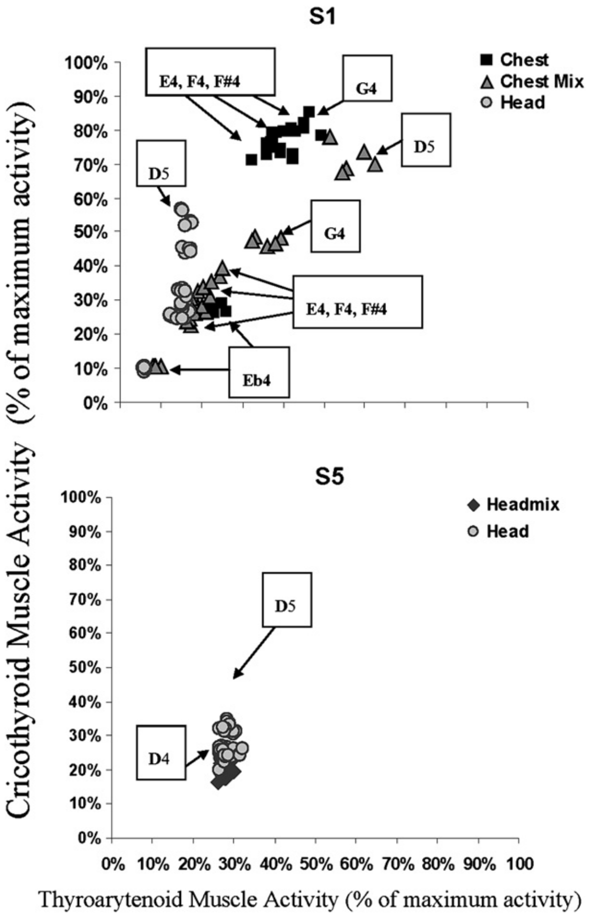

FIGURE 5. Muscle activation plots for subjects S1 and S5 showing percent of maximum thyroarytenoid and cricothyroid activity by frequency and register.

The expectation was that the tilt of the line for pitches produced in head voice would be the steepest and positioned furthest to the left and that the data collected in the other registers would gradually decrease in tilt and be positioned further and further to the right. Subject S5's data support this model; subjects S1's data also support this model if only the pitches produced in all three registers are considered.

Statistical analyses were not performed on the EMG data because both TA and CT muscle activity showed a relationship to pitch and were observed to vary with both pitch and register. In addition, subjects phonated over different pitch ranges (eg, Eb4–F4, F4–C5, and D4–D5). Therefore, it was not possible to combine the individual subject TA and CT muscle activity data into group means (and standard deviations) for statistical analysis.

Adduction rating of VPs

Figure 6 shows the average ratings of vocal fold adduction (based on the size of VPG) as a function of pitch and register for four subjects for whom videoendoscopic data were obtained. Subject S1 produced seven pitches in three registers; however, it was not possible to visualize the vocal folds during production of the two highest pitches because of changes in vocal tract

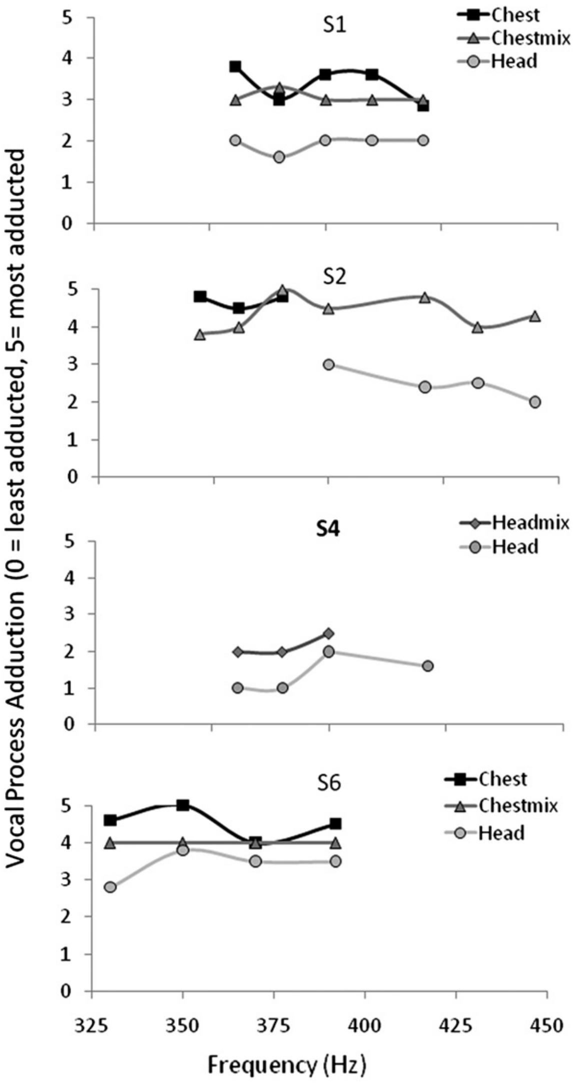

FIGURE 6. Individual mean vocal processes adduction ratings by frequency and register for S1, S2, S4, and S6.

shape used to produce these pitches in chestmix or chest register. As a result, data from five pitches were provided here.

As seen in Figure 6, subjects usually increased adduction of the VPs as they produced the same pitch in a heavier register. All subjects exhibited the greatest adduction for chest, then chestmix, then headmix, and least for head. This trend is seen in the group data (Figure 7 and Table 3) and in the individual data (Figure 6). Average adduction rating during production of pitches produced in head register was 2, in headmix 2.5, in chestmix 3.5, and in chest 4.3. Although adduction changed as a function of register, it did not change as a function of pitch.

Table 3 shows the group means and standard deviations for VPs adduction ratings across all subjects. Pitches produced in chest had greater adduction than those produced in chestmix (not statistically significant). Pitches produced in chest had greater VPG adduction than those produced in headmix and head (statistically significant at <0.01). Pitches produced in chestmix had greater adduction than those produced in headmix (statistically significant at 0.5) and pitches produced in both chestmix and headmix showed greater vocal fold adduction than those produced in head (not statistically significant).

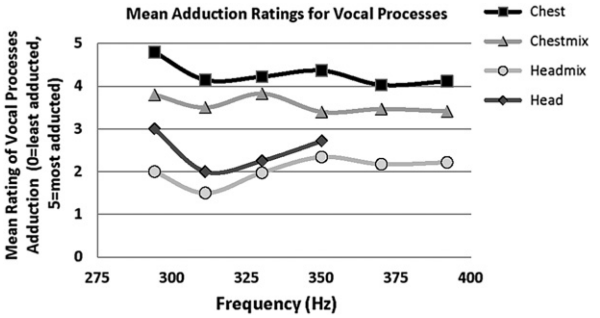

FIGURE 7. Mean adduction ratings for the vocal processes gap during chest, chestmix, headmix, and head by frequency and register for all subjects, 0 = least adducted, 5 = most adducted.

Figure 8 shows video stills for S1 during production of G4 (392 Hz) and F4 (370 Hz) in chest, chestmix, and head. Note the increasing size of the VPG from chest to chestmix to head for both frequencies. Also, note that the vocal folds appear thinner in chest than chestmix. This is likely because of the greater levels of CT activity observed for chest than chestmix at these frequencies (see Figures 7 and 8, S1). The data provided here show that singers increase adduction of the VPs as they produce the same pitch in a heavier register and adduction for chestmix was, as hypothesized, less than for chest but greater than for headmix and head.

Results from inter- and intrajudge reliability testing via Cohen's kappa coefficient for the video still ratings were 0.56 and 0.58 for intrajudge reliability and 0.59 for interjudge agreement, indicating moderately good agreement.[26]

DISCUSSION

The purpose of this study was to determine if female commercial singers produce midrange pitches in chestmix register by maintaining or increasing adduction of the VPs and by engaging the TA muscle to a greater degree than they would to produce head register.

Given that a register is defined as a series of frequencies that are perceived to be of similar quality and produced in a similar physiological manner,[1,2] the results of this study suggest that in addition to the more clearly defined and understood registers (chest and head), there are additional registers (referred to in this study as chestmix and headmix) that were perceived as having a distinct quality by the expert judges and were shown to have distinct acoustic features in regards to spectral tilt and the energy in the F_0. In addition, chestmix and headmix tokens were produced with consistent differences in both the degree of VPG and TA muscle activity. Unlike chest and falsetto, which do not appear to require training, the singers' ability to produce chestmix or headmix appeared to be related to type of singing training. In general, those with commercial singing training were less likely to produce headmix, whereas those with classical singing training were less likely to produce chestmix.

Our spectral findings for chest and head register are consistent with those reported in the literature, which found that chest

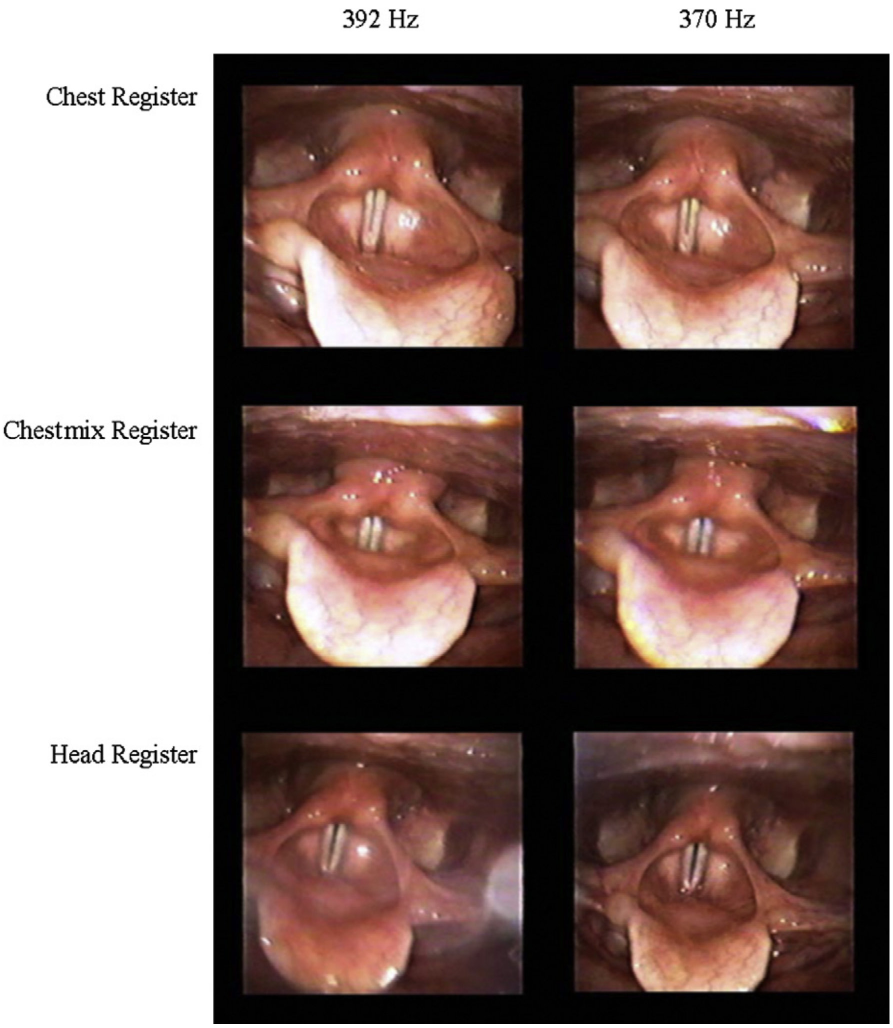

FIGURE 8. Video stills of vocal processes gaps during production of 392 Hz (G4) and 370 Hz (F4) tones in chest, chestmix, and head register by S1.

phonation is characterized by greater energy in the mid and upper frequency harmonics, whereas falsetto and head voice are characterized by a weaker energy in the upper frequency harmonics.[6–9,13] The spectral results are also consistent with and add to the findings of Keidar et al,[4] which showed that the perception of the timbres associated with the chest and falsetto registers is related to the spectral tilt of the glottal source spectrum.

Our findings also appear to be consistent with the one study that examined the acoustics of middle voice. Large[16] examined the narrow band spectrums of five trained female classical singers during same pitch phonation on E4 in chest and middle voice. Middle voice showed less energy in the high frequency harmonics than chest. However, these data are difficult to interpret as the term "middle" does not indicate whether the mix was chestmix or headmix. However, because the subjects of Large[16] were classical singers and his findings are more consistent with the acoustic characteristics reported here for headmix, it seems reasonable to assume that the middle voice that Large[16] refers to was a headmix. Another study that examined the spectral characteristics of belt (chest), mix, and opera (head) in one trained female singer found that mixed voice had greater energy in the mid and upper harmonics than belt or opera.[11] Conversely, our data showed similar energy for both chest and chestmix in the mid and upper harmonics. Chestmix differed from chest only in the energy of the F_0, which was greater for chestmix.

Results from this study showed that TA muscle activity was greater during production of same pitch phonation in chestmix register than in headmix or head register, in the mid and upper frequencies. TA muscle activity for chestmix was substantially greater than for headmix or head in the upper frequencies (F4–D5). There were no productions perceptually rated as chest above G4 (392 Hz); thus, it is not possible to compare TA activity across all registers above this point. Although similar levels of TA muscle activity were observed for chestmix and headmix in the lower frequencies, both were less for chest but greater than head.

The finding of greater TA activity for chest than head was consistent with results from previous research that have examined chest and falsetto and chest and head contrasts.[10,17–20] There are few data on laryngeal muscle activity during headmix in the literature. However, Hirano[20] reported findings similar to ours (S4) for one female classical singer who showed greater

TA activity for middle voice than head but less for chest. Again, it is difficult to interpret this finding as the term middle voice was not clearly defined and there was no indication of the type of mix his subject produced. However, considering that the subject was a classical singer, it seems reasonable to hypothesize that the subject of Hirano[20] most likely produced a headmix.

There has been much speculation regarding the mechanisms of register control in the area of the primo passagio. Both classical singers and commercial singers seek to avoid abrupt register transitions. According Titze,[27] if a singer is to remain in chest as pitch increases, the TA muscle must remain active. He further suggests that the trained singer may offset the increased adduction caused by increased TA muscle activity by separating the VPs as pitch increases. Our data showed a substantial increase in TA muscle activity in the region of the primo passagio (F4–G4 or G4–A4 depending on voice type) for subjects S1 and S2 during the production of chestmix as compared with head. Chest voice showed an increase in activity in this region for only S1. The notion of increased TA activity and separation of the VP to remain in chest or chestmix as pitch increases is in opposition to what classical singers are believed to do to smoothly transition from chest to falsetto. Titze[27] has speculated that trained classical singers may gradually decrease TA activity, whereas they increase CT activity as pitch is increased and thus achieve a smooth register transition. Hirano[28] observed this for one trained male classical singer.

Results from this study seem to suggest an effect of type of vocal training. Singers with primarily classical training were less likely to produce registers other than headmix and head, whereas singers with primarily commercial training were more likely to produce chest, chestmix, and head but not headmix. In addition, singers with primarily classical training showed smaller ranges of TA muscle activity (25–38% of maximum), whereas those with commercial training showed a greater range of TA muscle activity (5–75% of maximum). This was particularly true for high pitch phonation. Many studies have compared trained versus untrained singers in regards to acoustic, aerodynamic, and videostroboscopic characteristics, but no study has compared classically trained singers with commercially trained singers. It may be that different types of vocal training result in different laryngeal muscle activity patterns.

Our finding of greater VP adduction for heavier registers was consistent with findings from previous research, which found greater vocal fold adduction for chest than head or falsetto[10,12–15,21–24]; Hertegard and Gauffin, 1995. Likewise, our data for chestmix are consistent with findings by Sundberg et al[11] who reported greater vocal fold adduction for belt than mix and the least adduction for opera in one trained female singer. Herbst et al[24] also reported differences in degree of VP adduction for naïve falsetto, countertenor falsetto, lyric chest, and full chest produced by one trained classical baritone. Herbst et al[24] referred to these vocal qualities as abducted falsetto, adducted falsetto, abducted chest, and adducted chest, respectively. Although differences in subject gender and register terminology make direct comparison of the findings from the Herbst et al[24] study and this study difficult, one can none the less see a similar pattern, greater vocal fold processes adduction and greater adduction overall is observed as a singer moves from a "lighter" register (eg, head or falsetto) to a "heavier" register (eg, chestmix and lyrical chest to chest or full chest).

The physiologic, acoustic, and perceptual data reported in this study all appear consistent with previously proposed models of register control. Titze[5] has speculated that the spectral tilt of the glottal source spectrum is related to the degree of glottal adduction and the amplitude of vibration. Our VP adduction data, as well as preexisting vocal fold adduction data for chest and falsetto, support this theory in that the degree of the VP adduction was observed to be related to spectral tilt and perceptual ratings.

To ensure that subjects produced the target registers naturally, intensity was not controlled. Controlling intensity risks adversely affected normal register production for a given subject. Because singers' voices vary in terms of use of the dynamic range (eg, some are dramatic and some are lyric) attempting to control intensity could possibly force them to sing in a way that was not natural for them. We also did not measure subglottic pressure. We assume that other respiratory, velar, or oral structures of the speech mechanism may also be undergoing adjustment. Other laryngeal muscles may be adjusting their activation levels as well. However, it was not within the scope of this study to examine these other variables. This study was limited to examination of modulation of the TA and CT muscles and the VPG associated with change in register.

SUMMARY

The data from this study lend support to the current register control theories, which suggest that vocal registers are controlled at least in part via changes in laryngeal muscle activity and vocal fold adduction.[4,5,23,25] In addition, the data showed a trend toward greater TA muscle activity and VP adduction for chest and chestmix than for headmix and head. In addition, the chestmix and headmix registers were found to be perceptually identifiable, different in degree of TA muscle activity and VP adduction and different acoustically. Although patterns of TA muscle activity across the registers were similar across subjects, individual subjects varied in the amount of TA muscle activity used to accomplish a given task and this finding may be an effect of either type or length of vocal training. Future studies investigating laryngeal muscle activity as a function of register should include simultaneous measurement of subglottal pressure and EMG to examine the possible role of subglottal pressure in pitch control across registers.

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Appendix. Training CD: Artist and Song List

Artists	Song List	Phrase
Examples of chest register		
1. Grace Slick	"White Rabbit"	"Go ask Alice, I think she'll know"
2. Liza Minnelli	"New York, New York"	"King of the hill"
3. Ethel Merman	"Anything Goes"	"Plymouth rock"
4. Cher	"Believe"	"Really don't think you're strong enough"
Examples of chestmix		
1. Ann Wilson (Heart)	"What About Love?"	"What about love, don't let it slip away"
2. Whitney Houston	"Savin' All My Love"	"Savin' all my love, yes I'm savin' all my love"
3. Barbara Streisand	"Evergreen"	"Time won't change the meaning of"
4. Reba McEntire	"You Lie"	"You Lie"
Examples of headmix		
1. Judy Collins	"Someday Soon"	"There's a young man that that I know"
2. Ella Fitzgerald	"Summertime"	"Summertime and"
3. Olivia Newton-John	"I Honestly Love You"	"And not my head"
4. Kathleen Battle	"Lord I Couldn't Hear Nobody Pray'n"	"I couldn't hear nobody pray'n"
Examples of head		
1. Sarah Brightman	"Phantom of the Opera"	"The phantom of the opera"
2. Joni Mitchell	"Big Yellow Taxi"	"Don't it always seem to go"
3. Joan Baez	"Where have All the Flowers Gone?"	"Long time passing"
4. Renee Fleming	"Summertime"	"Summertime"