Physiological and acoustic characteristics of the female music theater voice

Tracy Bourne
University of Ballarat, Arts Academy, Ballarat, Victoria 3353, Australia

Maëva Garnier[a)]
School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia

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Three Music Theater vocal qualities ("chesty belt," "twangy belt," and "legit") were investigated in female singers at their overlap range, between F#4-D5 (∼370-600 Hz). Six experienced Music Theater singers performed each quality on two different vowels ([e], [ɔ]). Audio and electroglottographic (EGG) signals were recorded as well as the vocal tract impedance. In chesty belt and twangy belt, singers systematically tuned the frequency of their first vocal tract resonance ($R1$) to the second harmonic ($2f_0$) up to C5. $R1$ remained lower in frequency for the legit quality. No tuning of the second vocal tract resonance ($R2$) was observed in any of these qualities although $R2$ frequency was significantly higher in both belt qualities than in legit. Closed quotient, degree of symmetry of the EGG waveform, sound pressure level (SPL) and the energy of the spectrum above 1 kHz were significantly greater in chesty belt than in legit but not significantly different between chesty belt and twangy belt qualities. A fourth quality ("mix") was explored in three singers. Different production strategies were observed for each singer, with values of spectral, glottal and vocal tract descriptors found in between those measured for legit and chesty belt qualities.
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I. INTRODUCTION

Female professional Music Theater singers are expected to master the vocal qualities: belt, legit, and mix. These terms are commonly used by expert teachers (Bourne and Kenny, 2008; Bourne *et al.,* 2010) and within the Music Theater profession, although they are not yet well defined from a physiological and acoustic point of view. This study aims to provide objective measurements to characterize and compare the laryngeal behavior, the vocal tract adjustment and spectral features of these Music Theater qualities.

Most research on the acoustics of the singing voice has focused on classical and operatic singing. However, there have been some recent studies of nonclassical styles (country, pop, Broadway, Music Theater, R&B, jazz, rock, and blues), increasingly referred to as contemporary commercial music (CCM) vocal styles (Lovetri, 2008). CCM singing styles can be distinguished from classical singing by the regular use of amplification, a greater emphasis on lyrics and textual comprehension by the audience, and frequent employment of the voice quality described as "belt" (Lovetri, 2002; AATS, 2008).

Perceptually, belt has been described as a projected sound with "brightness," "ring," and "forward," speech-like vowels (Stanley, 1929; Osborne, 1979; Estill, 1980; Edwin, 2004; AATS, 2008; LeBorgne *et al.,* 2010) in contrast to the "covered" sound and "back" vowels of the classical voice. However, the genre of CCM is broad, and the term belt actually relates to a range of different sounds (Lovetri, 2002; Popeil, 2007). In fact, there is considerable disagreement among CCM experts about the distinctive features of belt, some arguing that belt is not always loud (Edwin, 2002; Popeil, 2007; LeBorgne *et al.,* 2010), that belt has no vibrato (Estill, 1980; Miles and Hollien, 1990), or that the degree of vibrato may be a stylistic choice (Bourne and Kenny, 2008; LeBorgne *et al.,* 2010), that belt is intrinsically a nasal quality (Miles and Hollien, 1990) or not (Bourne and Kenny, 2008; LeBorgne *et al.,* 2010).

Acoustically, the belt quality has shown increased energy in the high frequencies of the spectrum (Bestebreurtje and Schutte, 2000; McCoy, 2007) and higher first formant frequencies (F1) compared to classical singing (Sundberg *et al.,* 1993). Proximity between F1 and the second voice harmonic ($2f_0$) has been reported on [a] and [ɔ] vowels in a female Music Theater singer (Schutte and Miller, 1993), suggesting that belters may tune the first vocal tract resonance ($R1$)[1] to the second voice harmonic ($2f_0$). Such tuning has been observed over the same range in Bulgarian singing (Henrich *et al.,* 2007), a musical style that shares some similarities in timbre with the female belt sound.

Physiologically, the belt quality has been characterized by higher values of the laryngeal closed quotient and higher levels of subglottal pressure than for classical singing (Estill, 1980; Sundberg *et al.,* 1993; Bjorkner *et al.,* 2006; Barlow and Lovetri, 2010), supporting the argument by some singing teachers that female belt is produced by raising the transition pitch from 'chest register" to "head register" by up to an octave (Schutte and Miller, 1993; Bestebreurtje and Schutte,

[a)]Author to whom correspondence should be addressed. Also at: Department of Speech and Cognition, GIPSA-lab (UMR 5216 CNRS/Grenoble INP/UJF/U. Stendhal), 961 rue de la houille blanche, BP 46, 38402 Grenoble Cedex, France. Electronic mail: maeva.garnier@gipsa-lab.grenoble-inp.fr

2000; Miller, 2000). This hypothesis could be translated physiologically as the extension of the laryngeal mechanism M1[2] over the overlap range of M1 and M2, where classical sopranos choose to sing in M2 instead of M1.

Singing experts have suggested that belt articulation requires a higher and more forward tongue than for classical singing (Miles and Hollien, 1990; Burdick, 2005; Bourne and Kenny, 2008). The belt vocal tract shape has been compared to a megaphone (Titze and Worley, 2009) because of the more constricted pharynx, higher larynx position, and more opened mouth observed in this vocal production (Lawrence, 1979; Estill, 1980, 1988; Yanagisawa *et al.,* 1983; Sundberg *et al.,* 1993; Lovetri *et al.,* 1999; Edwin, 2004; Balog, 2005). The configuration of a narrow vocal tract and wide mouth opening is consistent with the higher F1 values reported in belt compared to classical singing (Sundberg *et al.,* 1993). However, one study suggests that some singers can also produce belt with a relatively low larynx and wide pharynx (Lovetri *et al.,* 1999).

Perceptually, there appear to be different kinds of belt, described by singing teachers and experts of CCM styles as "traditional belt," "heavy/weighted/chesty belt," "speech-like belt," or "twangy belt" (Popeil, 2007; Bourne and Kenny, 2008). However, scientific studies of the acoustic and physiological features of belt have not made that distinction between belt qualities, neither has any study compared and characterized objective differences. In particular, it remains an open question whether belt is an intrinsically twangy quality or whether twangy belt is actually a subcategory of belt. While twang has not been specifically studied in Music Theater singing, it has been explored in country singers (Cleveland *et al.,* 2001), stage actors (Nawka *et al.,* 1997), in a single female non classical singer (Sundberg and Thalen, 2010), and in relationship to voice efficiency (Titze, 2001; Titze *et al.,* 2003). Twang has been associated with higher values of the closed quotient (Titze *et al.,* 2003; Sundberg and Thalen, 2010) higher subglottal pressures (Sundberg and Thalen, 2010), constriction of the aryepiglottic area (Yanagisawa *et al.,* 1983; Story *et al.,* 2001; Titze, 2001; Titze *et al.,* 2003), widening of lips (Story *et al.,* 2001), higher frequencies of F1 and F2 (Story *et al.,* 2001; Sundberg and Thalen, 2010), nasalization of some vowels (Story *et al.,* 2001), and spectral enhancement around 3 kHz (Yanagisawa *et al.,* 1983; Nawka *et al.,* 1997).

Very few studies have been conducted on Music Theater voice qualities other than belt. In particular, no objective measurements have been made of the legit quality. We only know from the descriptions of expert teachers that legit is grounded in the classical tradition, sung largely in "head" register for female singers with "back" vowels and reported over a greater pitch range than belt (Edwin, 2003; Balog, 2005; AATS, 2008; Bourne and Kenny, 2008).

Likewise, no studies have characterized the laryngeal behavior of the CCM mix voice. Several studies of the classical "voix mixte" (Castellengo *et al.,* 2004; Lamesch *et al.,* 2007) have suggested that it can be produced either in M1 or in M2 laryngeal mechanism but never in an intermediary mechanism. Instead singers slightly modify their vocal effort and vocal tract adjustment so that the resulting sound is similar to the usual quality of the other laryngeal mechanism. Sundberg *et al.* (1993) found in a single female subject that mix demonstrated features of both classical and belt singing: voice energy was enhanced in high frequencies and first and second formants were measured at higher frequencies, similar to belt production. On the other hand, subglottal pressure and SPL were measured at moderate values closer to operatic singing.

This review of current knowledge on the female Music Theater voice raises the following questions about the characteristics of these vocal qualities:

(1) How do belt and legit qualities differ in terms of laryngeal behavior? Are there significant variations of glottal behavior over the frequency range of each quality?
(2) Are there any differences in vocal tract resonance tuning and source-filter interaction between belt and legit?
(3) Are there fundamentally different kinds of belt? In particular, is belt intrinsically twangy or does twangy belt differ significantly from chesty belt?
(4) What are the glottal behaviors and vocal tract adjustments underlying mix quality?

To answer these questions, six experienced Music Theater singers were recorded. Audio and electroglottographic signals were recorded on sustained pitches, together with the frequencies of the first two vocal tract resonances, for two types of belt (chesty and twangy), legit, and mix qualities, on two vowels: [e] and [ɔ].

II. MATERIAL AND METHOD

A. Subjects

The subjects for this study were six female Australian Music Theater singers; four of them professional (Subjects S1, S2, S3, S4) and two of them advanced tertiary level students specializing in Music Theater singing (subjects S5 and S6). Their details are summarized in Table I.

B. Task

Singers were asked to sustain a single note for 4 s with no change in pitch, loudness or vowel articulation and with limited vibrato.

This study aims to compare different qualities at similar levels of comfort versus effort across singers. Four increasing pitches were explored over the overlap range of belt or legit qualities. This overlap range varied between singers depending on their vocal classification and their belt range. It was determined from the highest reported belt note of each singer being C5 for four singers, D5 for singer S1, and B4 for singer S6 (see Table I).

Five measurements were made of each pitch, for two mid vowels pronounced as monophthongs in Australian English: [ɔ] (as in *poor*) and [e] (as in *head*). This procedure was repeated for each quality: chesty belt, twangy belt, and legit, beginning with the quality that was most comfortable for the singer. No technical instructions were given to singers on how to produce these qualities. An additional quality, mix, was investigated in singers S1, S5, and S6. These three

TABLE I. Details of 6 singers.

Subject	Experience	Training	Overlap range of belt and legit qualities
S1	Classical soloist	10 years (classical and short course in CCM) M.Mus (voc)	A4-D5
S2	Ensemble and solo MT	11 years (classical and CCM) B.Arts (MT)	G4-C5
S3	Ensemble MT	7 years (mostly CCM) B.Arts (MT)	G4-C5
S4	Soloist MT	30 years (classical and CM)	G4-C5
S5	MT tertiary student	6 years (CCM)	G4-C5
S6	MT tertiary student	5 years (classical and CCM)	F#4-B4

singers understood this term and were able to demonstrate a noticeably different sound from the other three qualities.

Audio samples of musical phrases are provided as supplementary material online to illustrate the four qualities investigated in this study.[3] These examples were produced by the singer S1 with the highest or sustained pitch at C5. These files are given as perceptual examples, as they were recorded after the experiment with different material and conditions.

All singers were given 10 min to warm up and were instructed to take regular breaks during the 1 h recording session. Subjects were also provided with water throughout the session to keep their voices hydrated.

C. Recordings and analysis

One 1/4-in. pressure microphone (Brüel and Kjær 4944-A) was attached to the front of a stand, alongside a small, flexible tube that was connected to a loudspeaker via an impedance matching horn. This acoustic source was used to excite the vocal tract with a synthesized broadband signal while the microphone recorded the response of the vocal tract to that excitation. The stand was adjusted for height so that the microphone and the tube rested gently upon the singer's lower lip during phonation. Signals from both microphones were amplified (Brüel and Kjær Nexus 2690), and digitized at 16 bits and a rate of 44.1 kHz using a Firewire audio interface (MOTU 828).

Spectral parameters and SPL were measured from the first clean second of phonation (no broadband excitation noise), and vocal tract resonances were measured during the second to fourth seconds of phonation. The electroglottographic signal was measured from the full 4 s of phonation.

The mean SPL and the average spectrum (with NFFT = 4096 points) were measured from the first second of phonation. The SPL was measured accurately, using the internal calibration signal of 1 V-RMS at 1 kHz delivered by the conditioning amplifier (Brüel and Kjær Nexus 2690), and knowing its V/Pa transduction coefficient. The α coefficient, defined as the ratio (in dB) of energy above and below 1 kHz (Frøkjaer-Jensen and Prytz, 1976; Sundberg and Nordenberg, 2006) was calculated from the long term average spectrum (LTAS) using MATLAB. So was the power ratio, defined as the energy difference in dB between the greatest harmonic level in the 0-2 kHz range and the greatest harmonic level in the 2-4 kHz range (Omori *et al.*, 1996),

During the final remaining 3 s of phonation, the first two vocal tract resonances were measured using a technique described by Epps *et al.* (1997) and Joliveau *et al.* (2004). During phonation, the vocal tract was excited at the lips via the flexible tube (internal diameter of 6 mm), using a synthesized broadband signal consisting of a sum of sine waves over the range of 200–3000 Hz spaced at 11 Hz (= 44.1 kHz/2^{12}). The nearby microphone recorded the vocal tract response to the excitation. Frequencies of the vocal tract resonances were detected manually from the maxima of the measured pressure ratios

$$\gamma = p_{\parallel}/p_{\mathrm{r}} \tag{1}$$

where $p_{\parallel}$ is the pressure spectrum measured with an open mouth, and p_{r} is the radiated spectrum measured at the lips with the mouth closed (performed during an earlier calibration procedure).

The electroglottographic signal was simultaneously recorded with a two-channel electroglottograph (Glottal Enterprises EG2) using medical gel to improve electric contact between the skin and the electrodes. Electrodes were placed on both sides of the thyroid cartilage while the singer was singing in her comfortable middle range. The best placement of the electrodes was found by monitoring the EGG waveform with an oscilloscope. Medical tape was used on each electrode, instead of the usual Velcro neck strap, to prevent the electrodes from moving down throughout the experiment. No automatic gain control was used.

Using MATLAB software, four parameters were extracted from the 4 s of EGG signal, using an 80 ms sliding window with no overlap:

(1) The mean fundamental frequency (f_0), with a standard autocorrelation method.
(2) The mean amplitude of the EGG signal, the average of which is highly affected by inter-individual differences in neck constitution (width, amount of fat, and muscles) and tissues conductivity. As a result, only intra-speaker variations of that parameter are meaningful and can be interpreted (mostly as variations in the amount of glottal contact, but also partly as vertical displacements of the larynx). To conduct statistical analysis, we normalized the amplitude of the EGG signal by its mean value as observed in the legit quality for each singer.

(3) The mean glottal open quotient (OQ), computed from the closing (positive) and opening (negative) peaks detected in the derivative of the EGG signal [DEGG, see (Henrich *et al.*, 2004)].
(4) The mean contact speed quotient (Qcs), defined as the ratio in amplitude of closing and opening peaks of the DEGG signal and describing the degree of asymmetry of the EGG waveform.

Because of a very bad skin conductivity, the EGG signal of S4 was too poor in quality to make accurate recordings of her glottal behavior. Consequently, glottal observations are reported for only five singers.

A two-way analysis of variance (ANOVA) with repeated measurements was conducted using SPSS® (Factor 1: quality, three levels: legit, chesty belt, twangy belt.[4] Factor 2: vowel, two levels: [e], [ɔ]). The main effect of the factor quality was tested first. Specific contrasts between chesty belt and legit qualities, and between chesty belt and twangy belt qualities, were also examined—applying Bonferroni adjustments—to determine whether voice parameters were significantly different between these qualities. Second, the statistical interaction between quality and vowel factors was tested to determine whether the difference in voice parameters among legit, chesty belt, and twangy belt qualities depended on the vowel. The results of these statistical analyses are reported at the bottom of Figs. 2 and 3. The conventional notation was adopted for indicating statistical significance: $*P < 0.05$, $**P < 0.01$, ***, $P < 0.001$, and *ns* (not significant) $P > 0.05$.

III. RESULTS

A. Comparison of legit and chesty belt qualities

1. Vocal tract resonances

$R1$ frequencies of legit productions varied relatively little over the investigated pitch range nor did they increase with pitch. They were never tuned to one voice harmonic (see Fig. 1).

In chesty belt, all the singers except S3 increased the frequency of $R1$ with pitch and closely adjusted it to the second voice harmonic ($2f_0$) up to C5 in both [ɔ] and [e] vowels (see Fig. 1). On average, $R1$ frequencies were 187 ± 48 Hz[5] higher in chesty belt than in legit over the pitch range considered (F#4-D5). However, such a significant difference in $R1$ was observed at all pitches for only two singers (S3 and S4). The other singers showed a significant difference in $R1$ from G#4 only.

Legit and chesty belt qualities did not differ by the presence or the absence of $R2$ tuning: in both qualities, $R2$

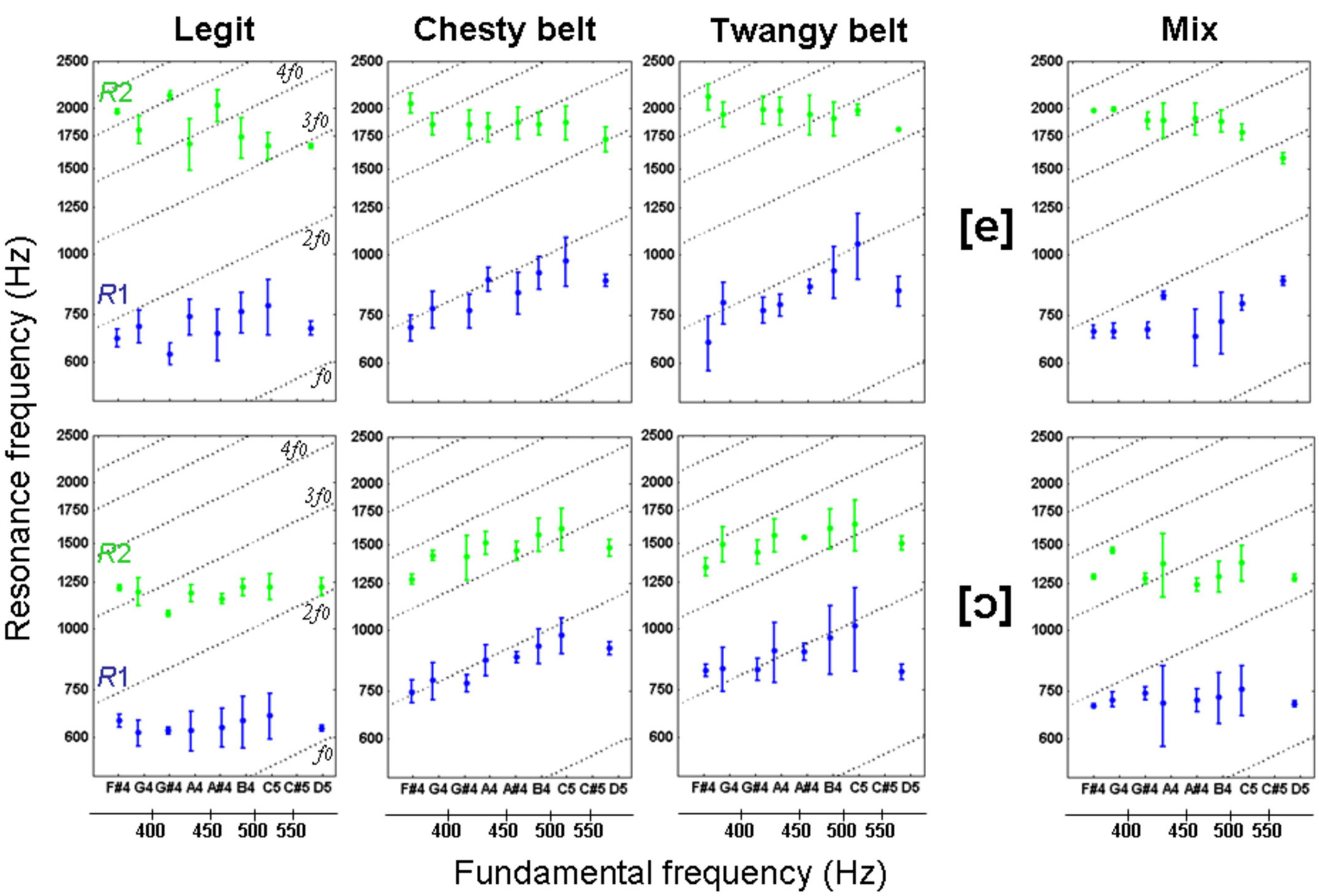

FIG. 1. (Color online) Comparison of resonance strategies in legit, chesty belt, twangy belt and mix qualities, for the two vowels studied ([e] and [ɔ]), as a function of f_0. Each vertical bar indicates for each pitch the mean value and the standard deviation of the two first resonances frequencies ($R1$ and $R2$) measured over the 6 singers (for legit and belt qualities) and over 3 singers (for mix). As singers did not all produce the same pitches (see Table I), mean values and standard deviations were calculated over a varying number of productions (from minimum 3 to maximum 18 productions). The dotted diagonal lines indicate the relationship $R = n f_0$. They visually emphasise how $R1$ is tuned to $2f_0$ in chesty belt and twangy belt.

frequencies were not found to be consistently tuned to one voice harmonic over the pitch range investigated (see Fig. 1). Only one singer (S4) was observed to tune the frequency of $R2$ to the third voice harmonic ($3f_0$) on [ɔ] vowels and in chesty belt. On the other hand, both qualities differed by their mean $R2$ frequency that was on average 205 ± 106 Hz higher in chesty belt than in legit (see Fig. 1).

2. Glottal behavior

Glottal observations are reported for five singers only, as the EGG signal of S4 was too poor in quality.

In these five singers, OQ values were significantly lower in chesty belt than in legit (by -0.21 ± 0.04), without any difference between the vowels [e] and [ɔ] (see Fig. 2).

The Qcs tended to be higher (i.e., the EGG waveform tended to be more asymmetrical) in chesty belt than legit (by 0.75 ± 0.67), but this effect was not found to be statistically significant (see Fig. 2).

No significant difference was observed in the amplitude of the EGG signal between legit and chesty belt productions, irrespective of the vowel (see Fig. 2).

3. Voice spectrum

For the six singers in this study, SPL was significantly higher in chesty belt than in legit (by 10.7 dB $\pm$ 4.3 dB) as were values of the α coefficient (by 4.4 ± 1.0 dB). These differences between legit and chesty belt qualities were similar for both vowels (see Fig. 3).

Values of power ratio also tended to be lower (i.e. energy in the 2−4 kHz region tended to be more enhanced) in chesty belt than in legit (by 6.4 ± 6.4 dB), but this difference was not found to be statistically significant (see Fig. 3).

B. Comparison of chesty belt and twangy belt qualities

As in chesty belt, $R1$ frequency in twangy belt was tuned to the second harmonic up to C5. This was observed in all singers for the vowel [e] and in four singers only (S1, S2, S5, and S6) for the vowel [ɔ]. No significant difference was observed in the average $R1$ frequency of chesty belt and twangy belt productions (see Fig. 1).

Again as in chesty belt, no tuning of $R2$ frequency with ascending pitch was observed in twangy belt (see Fig. 1). Nevertheless, twangy belt differed from chesty belt by 66 ± 37 Hz higher $R2$ frequencies on average.

No significant difference was observed between chesty belt and twangy belt qualities in the values of glottal parameters nor in the values of SPL and spectrum descriptors (see Figs. 2 and 3).

C. Mix quality in three singers

We recorded mix quality for three of the six singers: S1, S5, and S6.

1. Vocal tract resonances

The vocal tract behavior of singer S5 in mix was similar to chesty belt: She tuned $R1$ frequencies to the second voice harmonic ($2f_0$) but only up to A4. Her $R2$ frequencies were

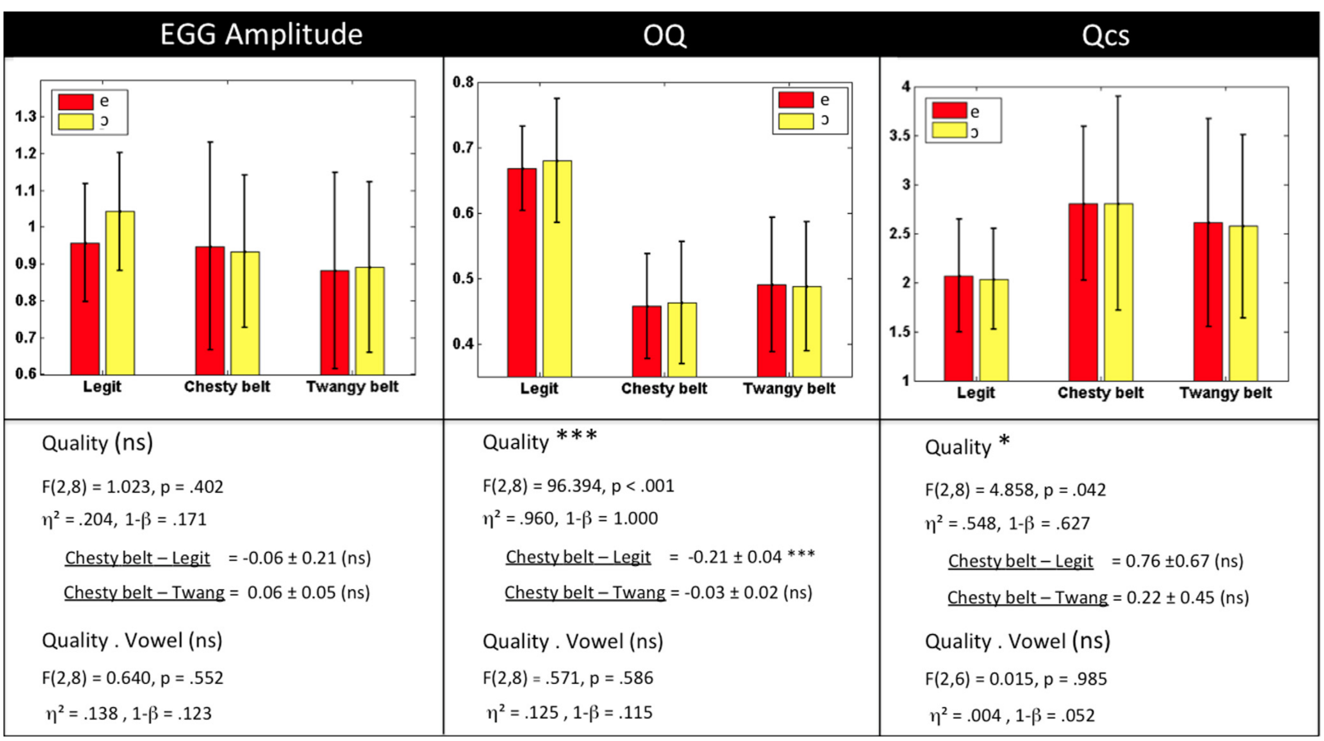

FIG. 2. (Color online) Comparison, on average over the pitch range explored, of the glottal behavior in legit, chesty belt and twangy belt, for the two vowels [e] (dark) and [ɔ] (light). Each bar represents the mean value and the standard deviation of each glottal parameter over the 5 singers S1, S2, S3, S5, and S6. At the bottom of each graph statistical results summarize whether the factor quality has a significant effect on glottal parameters, how the three qualities contrast from each other, and whether the influence of quality depends on the vowel.

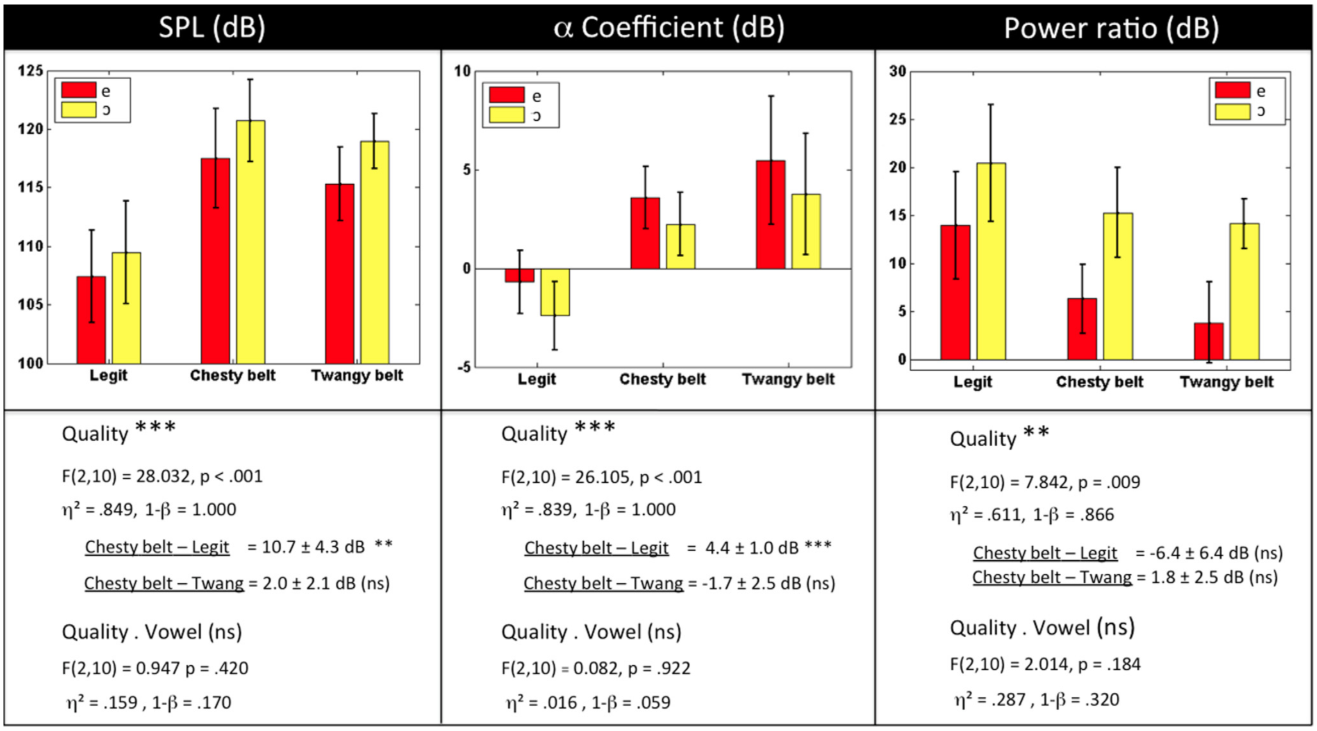

FIG. 3. (Color online) Comparison, on average over the pitch range explored, of SPL (at lips) and voice spectrum in legit, chesty belt and twangy belt, for the two vowels [e] (dark) and [ɔ] (light). Each bar represents the mean value and the standard deviation of each acoustic parameter over the six singers. At the bottom of each graph, statistical results summarize whether the factor quality has a significant effect on acoustic features, how the three qualities contrast from each other, and whether the influence of quality depends on the vowel.

in a similar range for both mix and chesty belt and were significantly higher than legit (see Fig. 4).

Conversely, the vocal tract behavior of singers S1 and S6 in mix was either closer to legit or intermediary to legit and chesty belt production. These singers did not demonstrate any tuning of $R1$ and $R2$ to voice harmonics in mix or in legit (see Fig. 4). Their $R1$ mix frequencies lay between chesty belt and legit (for S6) or closer to legit (for S1), while their $R2$ frequencies were close to those observed in legit for [ɔ]. There were no significant differences in $R2$ frequencies between legit, mix and chesty belt qualities on [e] vowels (see Fig. 4).

2. *Glottal behavior*

At the laryngeal level, two production strategies were also observed across the three singers.

For S1, her glottal behavior in mix was comparable to that of legit: OQ values were slightly lower in mix than in legit (by 0.07) but much higher than average values in chesty belt (see Fig. 4). Values of Qcs were much lower than values observed in chesty belt in a similar range to values observed in legit (see Fig. 4).

The glottal behavior of singers S5 and S6 in mix was more complex. For these two singers, OQ values in mix showed a discontinuous variation over pitch. Below A4-A#4, OQ values were observed in a low range close to that of chesty belt (∼0.5). Above A4-A#4, they were observed in a significantly higher range, close or similar to that of legit (∼0.63) (see Fig. 4).

3. *Voice spectrum*

Comparable patterns of voice production were again noted for S5 and S6 in mix with SPL values measured right in between those of chesty belt and legit qualities. For S1, SPL values were measured in a range closer to legit, consistent with her glottal behavior.

Values of the α coefficient were measured in between those of chesty belt and legit, except for singer S6's vowels [o], which were closer to the values of chesty belt.

IV. DISCUSSION AND CONCLUSION

A. Acoustic and physiological differences between belt and legit qualities

In this study, belt productions are characterized by higher $R1$ frequencies. This is consistent with higher F1 values reported in previous studies (Sundberg *et al.*, 1993) as well as with the raised larynx, more constricted pharynx and more open mouth described by previous studies (Lawrence, 1979; Estill, 1980; Yanagisawa *et al.*, 1983; Estill, 1988; Miles and Hollien, 1990; Sundberg *et al.*, 1993; Lovetri *et al.*, 1999; Edwin, 2004; Balog, 2005; Titze and Worley, 2009).

In addition, our results show that $R2$ frequencies are significantly higher in belt than legit. Again, this is consistent with the more forward position of the tongue taught by belting teachers (Miles and Hollien, 1990; Burdick, 2005; Bourne and Kenny, 2008) and with the more backward articulation of classical singing that is considered to influence the

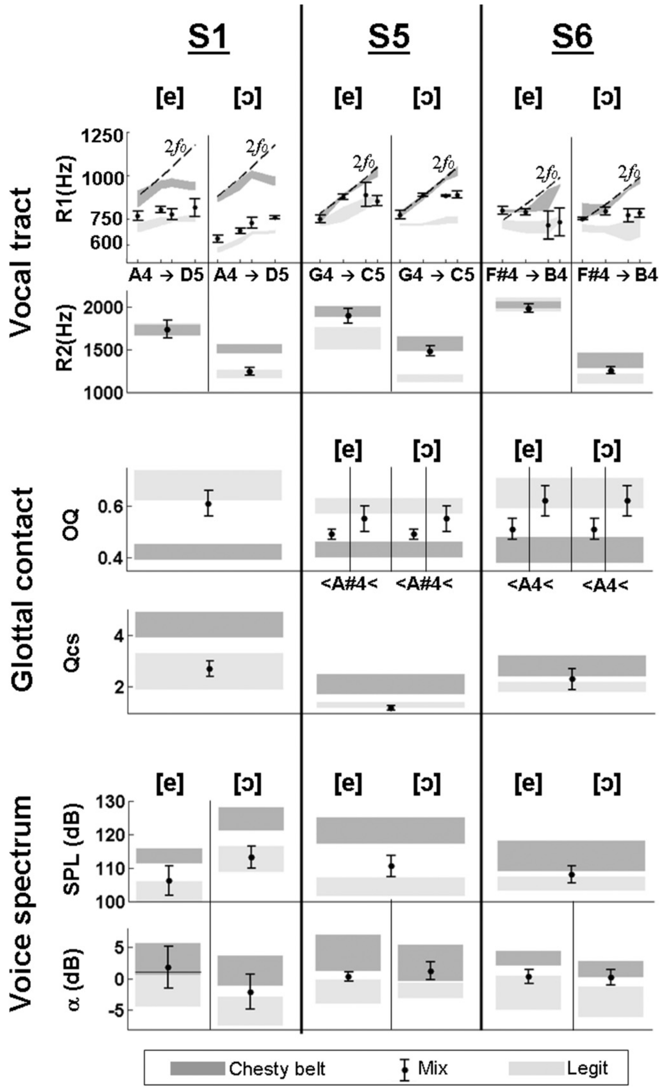

FIG. 4. Summary of the different individual strategies observed for the production of the mix quality by the three singers S1, S5, and S6. Error bars represent the mean value and standard deviation of voice descriptors in mix. Shaded areas represent the standard deviation of voice descriptors in legit (light grey) and in chesty belt (dark grey). On the top charts representing the variation of $R1$ frequencies with ascending pitch, the dashed diagonal lines indicate the relationship $R1 = 2f_0$. For the sake of simplicity, parameters values are averaged over the pitch range(s) where they were similar. Several values are displayed only where the parameter varied significantly between two pitch ranges (e.g., OQ values below and above A4-A#4 for S5 and S6) or between the two vowels considered (e.g., the α coefficient, $R2$ and the SPL for S1).

Music Theater legit quality (Edwin, 2003; Balog, 2005; AATS, 2008; Bourne and Kenny, 2008).

Our results did not show any tuning of $R1$ in legit, even over B4–D5 where classical sopranos usually start tuning $R1$ to the first harmonic (f_0) (Joliveau *et al.*, 2004; Garnier *et al.*, 2010). On the other hand, our results showed systematic adjustment of the $R1$ frequency to the second harmonic ($2f_0$) in belt, up to C5, for both [e] and [ɔ]. This is consistent with the proximity between F1 and $2f_0$ reported in a previous study (Schutte and Miller, 1993). No significant tuning of $R2$ was observed in legit or in belt, enabling singers to maintain phonetic distinction between vowel categories although the systematic $R1$:$2f_0$ tuning may cause a loss of the distinction in vowel height.

The $R1$:$2f_0$ resonance tuning in belt certainly helped production of the high sound pressure levels measured in all singers for this quality: around 120 dB at lips, 11 dB louder than in legit where no resonance tuning was observed.

This difference in voice intensity between belt and legit may explain the differences observed in glottal contact and in the voice spectrum. Indeed, the lower values of OQ measured in belt are consistent with greater vocal effort, as well as greater values of Qcs (i.e., more asymmetrical EGG waveform) and weaker values of the α coefficient (i.e., enhanced energy above 1 kHz) (Huang *et al.*, 1995; Henrich, 2001; Henrich *et al.*, 2005).

However, these differences may also be interpreted in terms of laryngeal mechanisms. Indeed, OQ values in belt were observed in a completely distinct range (0.43 ± 0.06) to values in legit (0.68 ± 0.08), supporting the idea that they correspond to two fundamentally different laryngeal behaviors. Furthermore, these two ranges correspond to typical OQ values in laryngeal mechanisms M1 and M2 (Henrich *et al.*, 2005). This interpretation in terms of laryngeal mechanisms would be consistent with weaker values of Qcs measured in legit. Indeed, the EGG waveform has been reported to be more symmetrical in M2 than M1 (Henrich, 2006; Roubeau *et al.*, 2009). On the other hand, Roubeau *et al.* (2009) described the amplitude of the EGG signal decreasing significantly (by about 40%) during the transition from M1 to M2 in female singers. In our data, belt and legit qualities did not differ in amplitude of glottal contact.

It is not clear whether the two distinct laryngeal behaviors that we recorded correspond to the laryngeal mechanisms M1 and M2 or whether the observed differences in glottal behavior relate to varying degrees of source-filter interaction and vocal effort. In any case, there is a strong relationship between the presence of $R1$:$2f_0$ tuning and the measured glottal parameters: Indeed, S3 in chesty belt demonstrated $R1$:$2f_0$ tuning up to A4 and a discontinuous change in OQ values at that pitch. The other singers present low OQ values up to their maximum belted note, around C5 ($\sim$1000 Hz), which corresponds to the maximum range of $R1$ frequencies in speech. This is also the pitch at which S1 cannot maintain $R1$:$2f_0$ tuning any further. This raises the question of whether the end of the $R1$:$2f_0$ tuning conditions the upper limit of the belt range, and whether the rare singers who can belt up to F5 have developed an articulatory strategy that enables them to continue increasing $R1$ higher than 1 kHz, just like some coloratura sopranos can extend the tuning of $R1$:f_0 tuning above C6, up to F#6 (Garnier *et al.*, 2010).

B. Subcategories of belt

No significant difference was observed between twangy belt and chesty belt qualities except that $R2$ frequencies were significantly higher in twangy belt than chesty belt for all singers. A consistent tendency was also observed across singers toward slightly lower SPL, higher OQ values, and more symmetrical EGG waveform in twangy belt, although this was not statistically significant. In previous studies, twang was related to higher F1 and F2 frequencies (Story *et al.*, 2001; Sundberg and Thalen, 2010), lower OQ values

(Titze *et al.,* 2003; Sundberg and Thalen, 2010), and enhanced energy around 3 kHz (Yanagisawa *et al.,* 1983; Nawka *et al.,* 1997). In this study, the frequency of $R1$, the open quotient and the power ratio did not distinguish twangy belt productions from chesty belt ones.

These different results suggest that chesty belt and twangy belt are not fundamentally different modes of production. Although chesty belt might correspond to a slightly louder and more "pressed" phonation than twangy belt, both qualities appear to be underlined by the same glottal behavior. Furthermore, both kinds of belt are comparable in terms of source-filter interaction as they both show a similar tuning of $R1$ to the second harmonic. Both qualities only differ significantly in vocal tract adjustment: The higher $R2$ frequencies measured in twangy belt are likely to correspond to a more forward position of the tongue. Further research involving articulatory measurements would be needed to test this hypothesis.

To conclude, singers may be able to slightly vary their voice quality when belting, by adding more or less twang, by varying vocal intensity, or by adopting a more or less "forward" articulation, but the small differences in vocal production between twangy and chesty belt qualities do not support the existence of subcategories of belt.

C. First conclusions about mix

For all three singers, glottal and vocal tract measurements in mix quality were indeed observed at values in between those measured for legit and chesty belt qualities. However, each singer adopted different strategies to achieve this outcome.

For S1, the mix quality appears to be a more "pressed" variation of legit. OQ values in mix were slightly lower than for legit but remained in a similar high range, so mix and legit qualities appear to be underlined by the same glottal behavior. This singer did not demonstrate any $R1{:}2f_0$ tuning in mix; nor was this tuning evident in legit. $R2$ frequencies, sound pressure level, and voice energy above 1 kHz were intermediary between legit and belt values but closer to legit.

For S5 and S6, the glottal behavior in mix was adapted with pitch, comparable to belt in the lower range and comparable to legit in the upper range. Indeed, OQ values of mix productions below A4 were similar to those of belt at this range. From B4, OQ values rise significantly, becoming closer to legit in value. This suggests that S5 and S6 changed their glottal behavior from A4 to B4.

Despite these similarities in glottal behavior, S5 and S6 differed in their resonance strategies to produce the mix quality.

S5 demonstrated a tuning of $R1$ to the second voice harmonic ($2f_0$) as she did in belt but only up to A4. This also corresponds to the pitch at which this singer changes glottal behavior. Furthermore, $R2$ frequencies were intermediary between legit and belt values but closer to belt. For S6, on the other hand, vocal tract adjustments in mix are closer to legit: No resonance tuning is observed and $R2$ frequencies were intermediary between legit and belt values but closer to legit.

Distinct differences in the vocal production of belt and legit were demonstrated by the six singers in this study, suggesting that technical and pedagogical approaches may need to differ for these styles. There were no significant differences between twangy belt and chesty belt except in the higher values of $R2$ frequencies for twangy belt.

The three singers who were able to demonstrate mix quality used different glottal and vocal tract strategies to produce a sound that was "in between" belt and legit. Because we have only measured a small sample of singers, these results can only be regarded as indicative. Further study on the CCM mix voice may give more information on typical glottal and vocal tract configurations for this style.

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[1]We use the term "formants" to refer to the usual estimation of vocal tract resonances from the radiated voice spectrum. We use the term "resonances" to refer to direct measures of the vocal tract impedance (Epps *et al*., 1997).

[2]Laryngeal mechanisms M1 and M2 are most commonly used in speech and singing and underlie "chest/modal" and "head/falsetto" laryngeal registers respectively (Roubeau *et al*., 1997). In mechanism M1, the thyro-arytenoid muscle is part of the vibrating mass of the vocal folds. Vocal folds are thick. Variations of f_0 are mainly determined by the stiffness of the folds, controlled by the contraction of the thyroarytenoid muscle. By contrast, the vocal folds are thinner in laryngeal mechanism M2 due to the assumed decoupling of the thyro-arytenoid muscle from the vibrating mass (Van den Berg, 1960; Hirano, 1982, Roubeau, 1993; Lacau St Guily and Roubeau, 1994). Variations of f_0 are mainly determined by the stretching of the folds, controlled by the contraction of the crico-thyroid muscle. There is an overlap pitch range in which singers can choose to produce the sound in either M1 or M2, depending on the desired vocal quality (Roubeau *et al*., 2009).

[3]See supplementary material at http://dx.doi.org/10.1121/1.3675010 for sound files.

[4]The mix quality was not included in statistical analysis because it was produced by only three singers.

[5]This standard deviation is calculated from the mean difference observed between chesty belt and legit qualities in each subject (thus over 6 values).

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