Vocal tract area functions and formant frequencies in opera tenors' modal and falsetto registers

Matthias Echternach
Institut of Musicians' Medicine, Freiburg University Medical Center, Breisacher Strasse 60, 79106 Freiburg, Germany

Johan Sundberg
KTH Voice Research Center, Speech Music & Hearing, Lindstedtsvägen 24, SE-10044 Stockholm, Sweden

Tobias Baumann
Department of Clinical Radiology, Freiburg University Medical Center, Hugstetterstrasse 55, 79106 Freiburg, Germany

Michael Markl
Department of Radiology, Medical Physics, Freiburg University Medical Center, Breisacher Strasse 60a, 79106 Freiburg, Germany

Bernhard Richter
Institut of Musicians' Medicine, Freiburg University Medical Center, Breisacher Strasse 60, 79106 Freiburg, Germany

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According to recent model investigations, vocal tract resonance is relevant to vocal registers. However, no experimental corroboration of this claim has been published so far. In the present investigation, ten professional tenors' vocal tract configurations were analyzed using MRI volumetry. All subjects produced a sustained tone on the pitch F4 (349 Hz) on the vowel /a/ (1) in modal and (2) in falsetto register. The area functions were estimated from the MRI data and their associated formant frequencies were calculated. In a second condition the same subjects repeated the same tasks in a sound treated room and their formant frequencies were estimated by means of inverse filtering. In both recordings similar formant frequencies were observed. Vocal tract shapes differed between modal and falsetto register. In modal as compared to falsetto the lip opening and the oral cavity were wider and the first formant frequency was higher. In this sense the presented results are in agreement with the claim that the formant frequencies differ between registers.
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I. INTRODUCTION

Vocal registers represent an important aspect of singing. The physiological correlates of modal and falsetto registers have been the subject of extensive research for more than 200 yr (Müller, 1840; Large, 1972, Hollien, 1974, Henrich, 2006). Clear differences have been found with respect to vocal fold oscillation patterns (Rubin and Hirt, 1960; Henrich *et al.*, 2005; Roubeau *et al.*, 2009; Echternach *et al.*, 2010a, 2011; Echternach and Richter, 2010, Herbst *et al.*, 2011). Thus, modal register is associated with greater oscillating vocal fold mass and more dominating vocalis muscle contraction, whereas falsetto seems associated with smaller oscillating vocal fold mass and a more dominating contraction of the cricothyroid muscle (Van den Berg, 1963; Hirano *et al*. 1970).

Voice source properties of the modal as compared to the falsetto register are characterized by a longer closed phase, a stronger voice source fundamental, and sharper flow pulses (Sundberg and Kullberg, 1998; Sundberg and Högset, 2001; Salomao and Sundberg, 2008; Salomao and Sundberg, 2009). By means of x-ray profile pictures Luchsinger (1949) was able to demonstrate that the configuration of the laryngeal ventricle differed between "head voice" (Kopfstimme) and falsetto. He found a greater adduction of the ventricular folds for a tenor's head voice than in his falsetto register. The term head voice refers to a vocal function for professional singing on stage above the region where usually registration events occur (*passaggio* region).

Recently, Tokuda *et al*. (2010) studied vocal registers by means of a computational four-mass body-cover model. The model had smooth geometry and was manipulated so as to produce transitions between chest and falsetto register phonation. Also, using a wave-reflection algorithm they modeled subglottal and supraglottal resonances. Their results suggested that register transitions are affected by vocal tract resonance, i.e., by articulatory configuration.

Several studies of articulatory configurations associated with vocal registers have been carried out in singers under *in vivo* conditions. However, these studies are limited either with respect to how much of the vocal tract was visualized, the number of subjects, and/or the specific vocal tasks used. For example, Tom *et al*. (2001) examined vocal tract shape differences between modal and falsetto using computed tomography (CT). Their single subject was a

TABLE I. Subject age, current repertoire and classification.

Subject	Age	Current repertoire	Classification
1	34	Werther (Werther, Massenet), Rudolfo (Boheme, Puccini)	national
2	30	Tamino (Zauberflöte, Mozart), Idamante (Idomeneo, Mozart)	national
3	37	Goro (Butterfly, Puccini), Mime (Rheingold and Siegfried, Wagner)	national
4	31	Tamino (Zauberflöte, Mozart), Aufidio (Lucio Silia, Mozart)	national
5	37	Bucklaw (Lucia, Donizetti), Loge (Rheingold, Wagner)	national
6	25	Varo (Ezio, Gluck), Nencio (L'infedelta delusa, Haydn)	international
7	32	Siegmund (Walküre, Wagner), Froh (Rheingold, Wagner)	international
8	45	Cavaradossi (Tosca, Puccini), Pinkerton (Butterfly, Puccini)	international
9	30	Monostatos (Zauberflöte, Mozart)	national
10	43	Tito (Tito, Mozart), Tamino (Zauberflöte, Mozart)	international

counter-tenor who produced a tone in speech mode in modal register and at one octave higher in singing mode in falsetto register. They found that the dimensions of the oral cavity were increased when their subject changed from "comfortable speech" (presumably in modal register) to falsetto.

Magnetic resonance imaging (MRI) has been used to reconstruct the vocal tract in three dimensions. For example, area functions and associated formant frequencies for different vowels as produced by single subjects have been reported by Story *et al.* (1996, 1998, 2001). However, at the time of these studies the acquisition time for obtaining an image of one vocal tract was between 4 to 5 min. Thus, many single phonations had to be recorded and combined.

In previous studies we applied two-dimensional dynamic real time MRI for analyzing vocal tract changes during register transitions (Echternach *et al.*, 2008; Echternach *et al.*, 2010b,c). In one of these studies we analyzed 10 professional operatic tenors who sang ascending scales, starting in modal and then either shifting to falsetto or avoiding a register shift. The modal to falsetto transition was associated with only minor changes. When these singers avoided a register shift, on the other hand, major changes were observed, such as a lift of the uvula and a widening of the lip and jaw openings and of the pharynx (Echternach *et al.*, 2010b). However, these studies were limited to two dimensional images of the midsagittal plane.

If vocal tract resonances are relevant to registers, register changes should be accompanied by changes of vocal tract shape. The present study is an attempt to corroborate the findings of Tokuda *et al*. Articulatory and acoustic data were gathered from ten professional operatic tenors performing a carefully designed vocal task. The data were derived from three-dimensional *in vivo* MRI recordings as well as from audio, flow and Laryngograph signals.

II. MATERIALS AND METHODS

The subjects were the same ten professional operatic tenors analyzed in the experiment described above, in which dynamic real-time MRI was used (Echternach *et al.*, 2010b). Table I shows their age, current repertoire and classification according to the Bunch and Chapman criteria (Bunch and Chapman, 2000). At the time of the recordings none of them

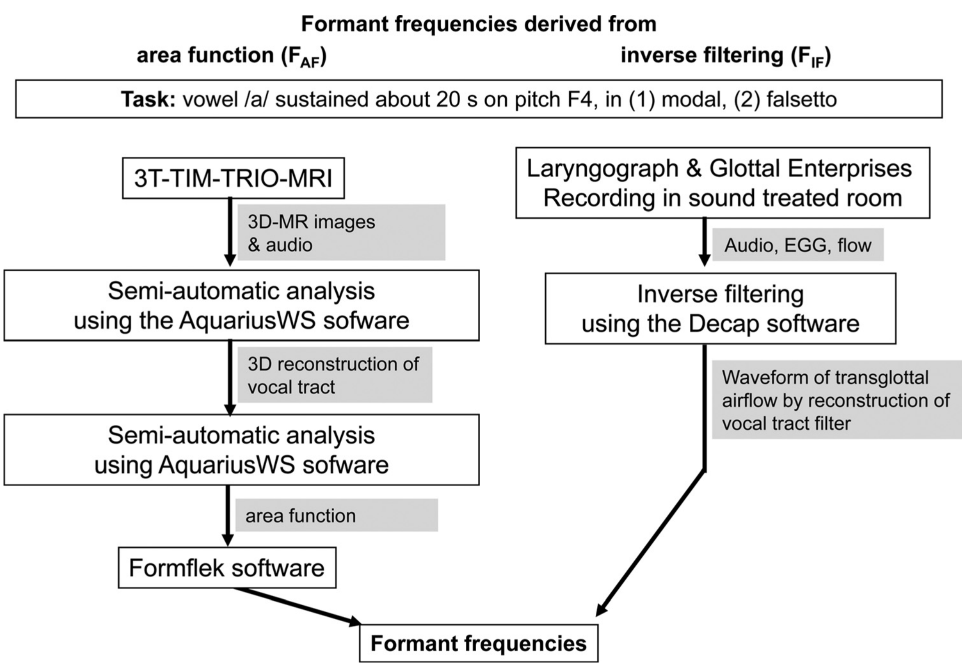

FIG. 1. Block diagram of the procedures used to estimate formant frequencies. The 3T-TIM-TRIO-MRI machine provided three-dimensional-MR images complemented by an audio system. The AQUARIUSWS software was used to derive three-dimensional vocal tract representation as well as the corresponding area function, the formant frequencies of which were determined by means of FORMFLEK software. Audio, EGG, and flow signals were recorded in a sound treated room by a combination of a Laryngograph and a Glottal Enterprises flow mask system. The audio and flow signals were inverse filtered using the DECAP software.

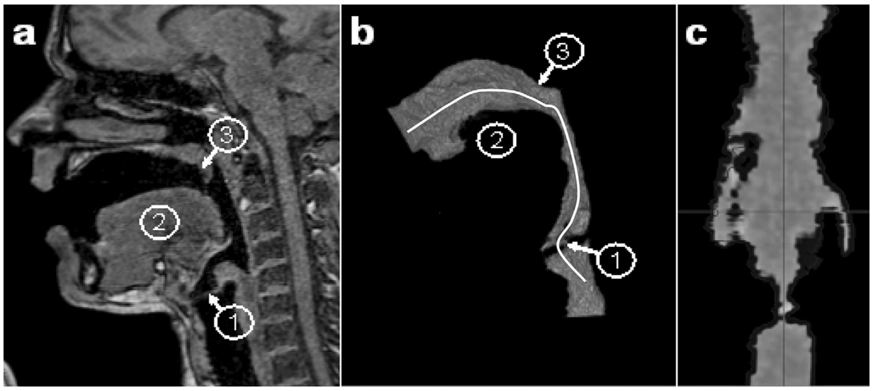

FIG. 2. Three images of the vocal tract for the vowel /a/ derived from MRI; 1, 2, and 3 mark the vocal folds, the tongue body, and the velum, respectively. (a) Vocal tract profile; (b) side view of a three-dimensional model of the same vocal tract with the semiautomatically constructed centerline. In (c) the volume is unwrapped along the centerline thus showing cross-sectional area.

complained of any vocal symptoms and vocal pathologies were excluded by videostroboscopy.

The subjects sustained a tone for 20 s, sung on the vowel /a/ (1) in modal register and (2) in falsetto register. The pitch of F4 (349 Hz) was chosen since professional tenors are able to phonate easily in both registers in this pitch region, frequently referred to as the *passaggio*. The subjects were asked to sustain the tone as consistently as possible. During the recording, two experts (both singers and otolaryngologists) checked that the register conditions were accurately produced. Additionally, after each sequence the subject was asked whether he thought that he succeeded in performing the register condition as intended. In a single case where the subject was not sure about this, the recording was repeated.

The analysis methods used are illustrated in Fig. 1. All subjects were examined radiologically with the 3.0 T TIM TRIO (Siemens, Germany) MRI device as described previously (Echternach *et al.*, 2008; Breyer *et al.*, 2009; Echternach *et al.*, 2010b,c). MRI volumetry with construction of the vocal tract area function was performed with the following parameters: three-dimensional GRE imaging, spatial resolution = 1.0 mm × 1.6 mm × 1.3 mm, TE = 1.67 ms, TR = 4.85 ms, flip angle = 12°, bandwidth = 300 Hz/Px, matrix = 250 × 142, field of view = 250 mm × 230 mm, GRAPPA = 2. Images were acquired in a sagittal plane in the center of the head.

In addition, a sound recording was made using a dual channel MR-compatible optical patient microphone (CONFON HP-SI 01, MR confon GmbH, Magdeburg, Germany). Two microphones (one recording sound and background MRI scanner noise and one recording scanner noise only) were mounted to the headphones worn by the subject. The signal was transmitted with two independent stereo channels. For noise cancellation, dedicated software (Digital Audio Presentation Center, CONFON DAP-center mkII+, MR confon GmbH, Magdeburg, Germany) was employed to subtract scanner noise from the sound signal so as to reduce the gradient noise. Like in our previous studies the subjects were provided with the audio signal over the headphones as acoustic feedback.

The datasets were transferred to a workstation equipped with a dedicated software suite for volumetric post-processing (AquariusWS, Terarecon, San Mateo, CA, USA). In a first step all connected dark regions representing air in the vocal tract were semiautomatically segmented by a region growing algorithm. Second, the air outside the body (beyond the anterior-most contour of the lips) and below the glottis was removed by manual clipping via the volume rendering display. If an open connection between the pharynx and the nasal cavity was observed ($n = 2$), the aerated nasal cavity was also removed by manual clipping at the position of the shortest distance between uvula and posterior wall (2 mm in both cases). In addition to the vocal tract, the resulting volume data set still included the teeth and parts of the palate due to ambiguities in signal values. Therefore, a manual correction was performed on each individual slice to remove

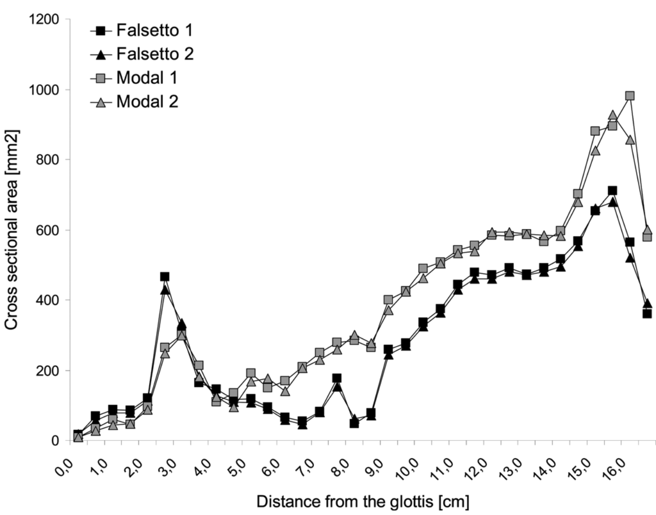

FIG. 3. Area functions obtained when subject 6 produced the same modal and falsetto conditions twice (gray and black symbols, respectively).

TABLE II. F_{AF} obtained when subject 6 repeated the same task.

	Falsetto 1	Falsetto 2	Difference		Modal 1	Modal 2	Difference	
Formant	Hz	Hz	Hz	%	Hz	Hz	Hz	%
1	521	441	− 80	− 15.4	609	673	64	10.5
2	1126	1114	− 12	− 1.1	1218	1294	76	6.2
3	2558	2450	− 108	− 4.2	2286	2358	72	3.1
4	3155	2943	− 212	− 6.7	3143	3211	68	2.2

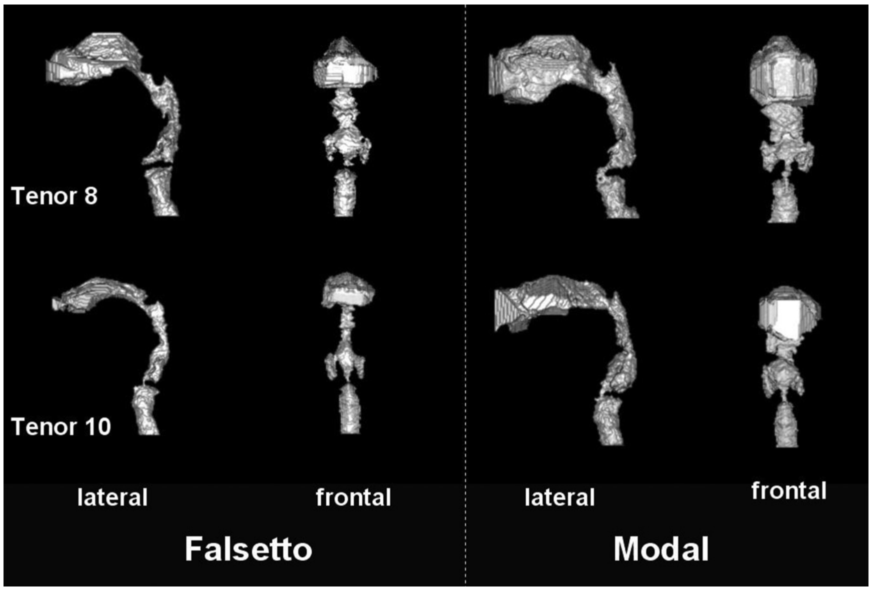

FIG. 4. Lateral and frontal view of three-dimensional vocal tract reconstructions of tenors 8 and 10 singing modal and falsetto register tones.

the palate and dental cavities. The teeth contours themselves, however, could not be removed since complementary data such as computed tomography was not available.

The final volume data of the vocal tract were consequently reprocessed with a vessel analysis tool (AQUARIUSWS) from the same software package as cited above. A line connecting centers of gravity was automatically drawn from between the central points of the glottis to the lip opening. Subsequently, this line was manually corrected to run through the midsagittal plane. The software automatically generates cross-sectional views perpendicular to the center line and calculates the area of the vocal tract on these views. This area was recorded at 0.5 cm intervals from the vocal folds to the lips to obtain the area function. Figure 2 illustrates the procedure used for deriving the area function from the three-dimensional-MRI data. The left panel shows the MRI profile, the middle panel shows the vocal tract contour together with the semiautomatically derived center line, and

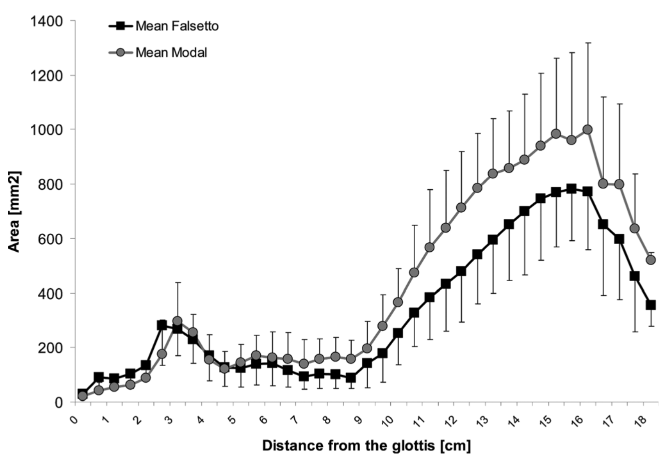

FIG. 5. Mean area functions for all subjects' modal and falsetto production of the vowel /a/. Bars represent one standard deviation.

the right panel illustrates the cross sectional area derived by converting vocal tract volume to area.

The formant frequencies associated with the area functions (F_{AF}) were calculated by the custom made FORMFLEK software (Liljencrants and Fant, 1975, Sundberg *et al.*, 1992). This software reads tables of cross-sectional areas representing the area function. Formant frequencies are calculated from these area functions, using the zeros in the transmission phase angle of the system as the criterion for resonance. In the calculations, the speed of sound propagation is set to 35 000 cm/s, thus approximating body temperature conditions. Viscosity and heat conduction losses are neglected. The program represents the area function by a series of cylindrical tube sections of variable lengths. These sections correspond to a series of cascaded inductance-capacitance links. The end correction l_0 added to the lip section is

$$l_0 = \frac{8}{3\pi}\left(\frac{A_0}{\pi}\right)^{1/2} = 0.85 r_0, \quad (1)$$

where A_0 and r_0 are the cross-sectional areas and the equivalent radius of the lip opening. The inner length correction (ILC) of any section of the network, is defined as

$$\mathrm{ILC} = 0.85 r\left(1 - 1.25\frac{r}{R}\right), \quad \text{for } \frac{r}{R} < 0.8 \quad (2)$$

and ILC = 0, elsewhere,

where r and R are the radii for the narrower and the wider adjacent cylinders. This means that an ILC was added to the narrower section at all points in an area function except where the radius ratio between two adjacent cylinders was greater than 0.8.

The consistency of the subject with regard to area function and the reliability of the area estimations were checked by asking subject 6 to repeat each of the falsetto and modal

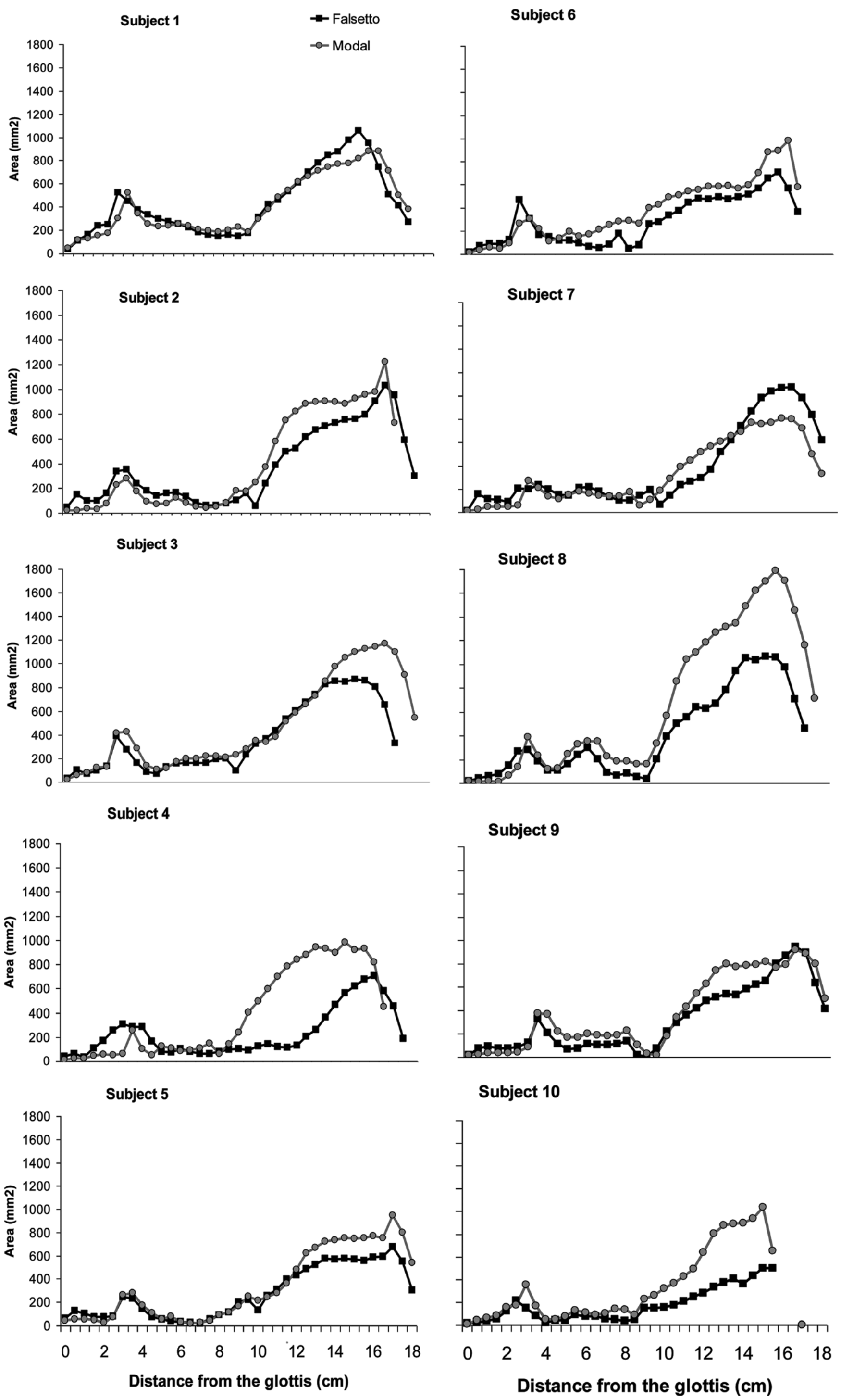

FIG. 6. Area functions for all subjects' modal and falsetto production of the vowel /a/.

conditions. The area functions thus obtained are shown in Fig. 3. The average of the absolute area difference was 8% (SD 6%, maximum 34%). The maximum difference was located in the oral cavity (45 mm^2 for falsetto and 124 mm^2 for modal register, respectively). The mean absolute F_{AF} discrepancy between the repeated measurements amounted to 6.2%, with the greatest discrepancy (15.4%) occurring for F1 in the falsetto condition (see Table II).

After the MRI recording session, the subjects were taken to a sound treated room where recordings were made for the inverse filtering analysis. As in the MRI session, the subjects were asked to sing in a supine position a sustained /a/ vowel on the same pitch of F4 in both modal and falsetto register. As in the MRI experiment, the tone was sustained for 20 s. The pitch of F4 was provided by the experimenter using a tuning fork. The vowel /a/ was used, because its F1 is much higher than the F0 value used. This substantially increases the accuracy of inverse filtering (Hertegård and Gauffin, 1994). After each sequence the register condition was confirmed by both the experimenters and the subjects. In one

TABLE III. F_{AF} for all subjects' modal and falsetto. The bottom lines show averages and standard deviations.

	*F*1		*F*2		*F*3		*F*4	
Subject	Modal	Falsetto	Modal	Falsetto	Modal	Falsetto	Modal	Falsetto
1	604	540	1216	1077	2632	2730	3452	3514
2	715	536	1155	995	2917	2575	3564	3146
3	659	652	1174	1150	2295	2359	3367	3360
4	648	408	1001	1109	2765	2355	3116	2946
5	582	537	1045	966	2475	2378	3114	3263
6	726	576	1443	1166	2503	2661	3519	3340
7	667	614	1168	1246	2626	2389	3167	3244
8	696	579	1165	1077	2560	2547	3007	2992
9	499	408	1032	1019	2627	2235	2927	2655
10	713	582	1357	1045	2514	2475	3692	3114
Mean	651	543	1176	1085	2591	2470	3293	3157
SD	71	80	139	85	169	155	260	246
p-value modal vs falsetto	0.0009		0.0664		0.1023		0.1014	

single case where the subject was not sure about the condition, the recording was repeated.

Using the Laryngograph MicroProcessor (sampling rate 16 kHz, Laryngograph, London, UK) combined with the MS 110 (pressure transducer PT-70, flow transducer PT-2, MA-1L Rothenberg mask, Glottal Enterprises, NY, USA), the audio signal, picked up at a distance of about 3 cm, the electroglottographic signal and the flow signal, picked up by a flow mask, were recorded simultaneously.

Applying the same strategies as described by Salomao and Sundberg (2008) the DeCap software (Svante Granquist, KTH, Stockholm, Sweden) was used for inverse filtering of the flow signal. Thus, the inverse filters were tuned manually and the program displayed the waveform and spectrum of the input as well as of the inverse filtered signal in quasi-real time. The derivative electroglottographic (dEGG) signal was also displayed. The EGG signal was delayed by a time interval reflecting the travel time of sound across the distance corresponding to the sum of vocal tract length and the distance to the microphone. A delay of about 0.7 ms mostly produced synchrony of the main dEGG discontinuity and the onset of the closed phase as represented by the flow glottogram. A section from near the middle of each recorded tone was selected. The inverse filtering procedure was to first place the formants, starting with the lowest, on spectrum envelope peaks and then to adjust their frequencies, paying attention to both the waveform and the spectrum of the filtered signal as well as to the synchrony of the negative peak of the dEGG and the discontinuity of the flow signal during the closing phase. An extra formant, probably corresponding to a mask resonance, was added near 1800 Hz. The criterion for the tuning of the filters was to obtain a ripple-free closed phase and a source spectrum envelope as free of local minima as possible. In cases of unexpected formant frequencies, the filter setting data were checked by synthesis using the custom-made Madde voice synthesis program (Svante Granqvist, KTH, Sweden). The procedure was to use the formant frequencies obtained to synthesize a tone having the same $F0$ as the subject. The filter settings were accepted only if they generated a vowel quality similar to that produced by the subject.

The reliability of the estimates of the four lowest formant frequencies ($F1$, $F2$, $F3$) derived from inverse filtering (F_{IF}) was checked by independently analyzing the same glottal periods from the audio and from the flow signals. These periods were taken from the modal register samples sung by six of the subjects. The mean absolute difference was 3.3% (maximum 6.6%), 7.3% (maximum 15.4%), and 3.0% (maximum 7.5%), for $F1$, $F2$, $F3$, respectively. The consistency of the subjects when performing the same task twice was examined by performing inverse filtering analysis of two takes of the same task performed by eight of the subjects. The mean absolute difference across subjects was 5.2% (maximum 14%), 8.0% (maximum 18%), and 6.3% (maximum 12%), for $F1$, $F2$, $F3$, respectively.

The formant frequency differences between modal and falsetto were tested statistically by means of paired *t*-tests.

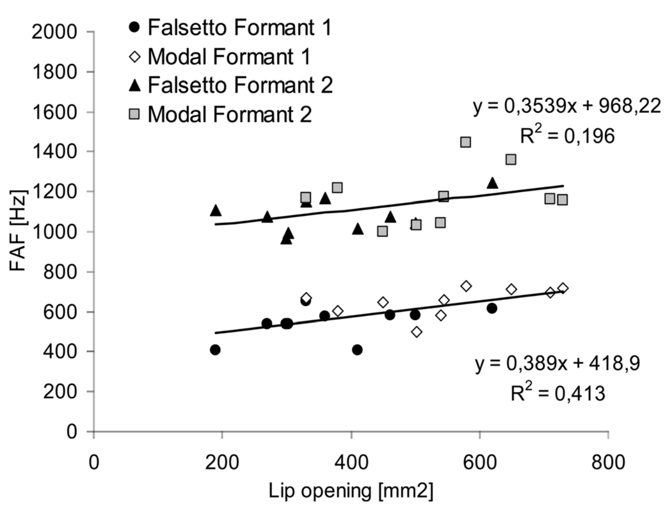

FIG. 7. $F1_{AF}$ and $F2_{AF}$ as function of lip opening. Trendlines and equations refer to modal and falsetto phonations pooled.

TABLE IV. F_{IF} for all subjects singing in modal and falsetto registers. The bottom lines show averages and standard deviations.

	$F1$		$F2$		$F3$		$F4$	
Subject	Modal	Falsetto	Modal	Falsetto	Modal	Falsetto	Modal	Falsetto
1	729	695	1235	1195	2216	2517	2821	2990
2	736	537	1264	1095	2671	2606	3101	2969
3	614	682	1032	1003	2494	2620	2776	3166
4	808	487	1315	1247	2250	2562	3039	3438
5	736	641	1169	1012	2396	2376	2815	2902
6	702	614	1249	1026	2524	2524	2916	3145
7	776	587	1255	1134	2416	2396	2659	2936
8	587	567	1120	1154	2214	2274	2760	2673
9	682	623	1198	1140	2494	2494	2776	2776
10	628	520	1114	1276	2214	2214	2936	2936
mean	700	595	1195	1128	2389	2458	2860	2993
SD	72	69	86	95	160	138	136	215
p-value modal vs falsetto	0.0143		0.0888		0.1387		0.0536	

The relationship between F_{AF} and the area of the lip opening was analyzed by means of the product-moment correlation coefficient (Pearson). The general level of significance was set at $\alpha = 0.05$.

III. RESULTS

In most subjects the vocal tract shapes derived from the MRI data showed clear differences between the registers, even though the nature of the differences varied between subjects, as can be seen in Fig. 4. By and large, these differences were greater in the oral cavity than in the pharynx, but both intersubject and intrasubject differences were found. For most subjects the lip opening and the oral cavity were larger in modal than in the falsetto register. Furthermore, in modal register half of the subjects showed a wider pharynx than in falsetto register. This pharynx widening concerned not only the anterior/posterior but also the lateral/medial dimension. The other half of the subjects, by contrast, used almost identical pharyngeal configurations during the two register conditions. In the velar and laryngeal regions only minor differences between registers were observed in the lateral/medial dimension.

The effects on the area functions of these vocal tract shape differences are illustrated in Figs. 5 and 6. In most subjects the oral cavity was larger in modal register, as expected. In the pharyngeal part, the cross-sectional area just above the larynx tube produced a peak in the area function in both registers (Fig. 5). This peak was caused mainly by the piriform sinuses and in most subjects appeared closer to the glottis in falsetto.

The formant frequencies predicted from the area functions differed somewhat between the registers (Table III): in most subjects, the first four formants were lower in falsetto than in modal register, even though only the difference in $F1_{AF}$ reached statistical significance. There was a positive correlation ($r^2 = 0.41$ and $r^2 = 0.20$, respectively) between the lip opening and the two lowest formants (Fig. 7). Also, $F1_{IF}$ was lower in falsetto as compared to modal (Table IV), even though many $F1_{AF}$ values were lower than the $F1_{IF}$ (mean $F1$ difference -50.5 Hz, $p < 0.05$; mean $F2$ difference $-31{,}4$ Hz, not statistically significant). With respect to $F3$ and $F4$, the two methods showed diverging results (Tables III and IV). $F3_{AF}$ and $F4_{AF}$ were lower in falsetto while $F3_{IF}$ and $F4_{IF}$ were higher. However, none of the differences was statistically significant.

It is sometimes assumed that singers prefer to tune formants to harmonic partials. In the present experiment all singers sang the same vowel on the same $F0$. In Fig. 8 the frequencies of the spectrum partials are compared with the formant frequencies derived by the two methods. $F1$ was closer to the second partial in modal than in falsetto register.

IV. DISCUSSION

We estimated the formant frequencies in tenors by two independent methods, inverse filtering and area function. The absolute difference averaged across subjects and registers amounted to 16, 12, 8, and 11% for formants 1, 2, 3, and

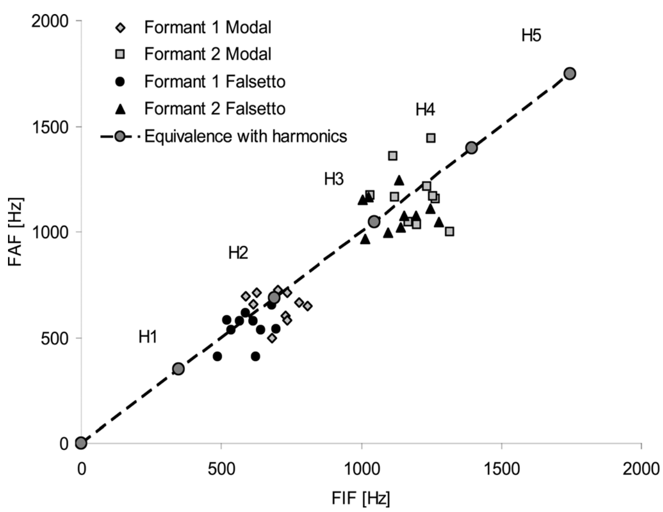

FIG. 8. F_{AF} and F_{IF} for formants 1 and 2 measured in the ten tenors in modal and falsetto register (gray and black symbols, respectively). The heavy filled circles represent the frequencies of the five lowest spectrum partials (H1, H2, H3, H4, H5). The diagonal line represents the case of complete agreement.

4, respectively. There are several potential sources of these discrepancies. First, it should be kept in mind that the data were derived from recordings made on different occasions and under differing conditions. The MRI data were collected in a noisy environment and the inverse filtering data in silent conditions. Furthermore, a source of error in the evaluation of the area function is the vocal tract reconstruction, which builds on an interpretation of the gray scale. Also, the length axis was quantized in steps of 0.5 cm and the FORMFLEK program assumes plane wave propagation, an assumption that becomes increasingly unrealistic with rising frequency. Both these factors are likely to reduce the accuracy of the higher formants. Teeth are not represented in the MRI material which could contribute to an overestimation of the first formant frequency.

Also, the flow data used for the inverse filtering were associated with some potentially relevant limitations. They were collected while the subjects were wearing a flow mask, which would have affected their auditory feedback and may also have limited the freedom of jaw opening. The subject could also have found the EGG electrode collar distracting. Inverse filtering analysis builds on the assumption that the transfer function of a tube resonator is predictable, given the resonance frequencies and bandwidths. A nonlinear interaction between filter and transglottal airflow may introduce errors in the formant estimates. This interaction should be particularly important and cause voice instability when the first formant frequency matches that of a partial. However, as shown in Fig. 8, in the cases where such a match was found there was no voice instability and the area function and inverse filtering estimates of $F1$ agreed.

With respect to the area functions, great interindividual differences were observed, apparently resulting in formant frequency differences, and possibly related to anatomical differences. Yet, some systematic differences were also found between the registers. Thus, in modal as compared to falsetto the oral cavity and the lip opening were wider in most subjects. These observations agree with those made in a previous investigation when the same ten singers sang an ascending scale pattern ending either as they would do on stage or ending in falsetto (Echternach *et al*., 2010b). Thus, the subjects seem to have behaved similarly when singing a scale and when sustaining a tone. However, subject 7, the only Heldentenor, had a wider lip opening and a wider frontal part of the oral cavity in falsetto. The size of the oral cavity was quite large in subject 8, particularly in modal register. This may be a response to this subject's tonsil hypertrophy. Tom *et al*. (2001) found that the dimensions of the oral cavity were increased when their subject changed from "comfortable speech," presumably produced in modal register, to falsetto register. This discrepancy with our finding may very well be an effect of the great $F0$ difference in their study between the modal and falsetto tones. Also, it may be relevant that their subject was a counter-tenor while ours were tenors.

Both the area function and the inverse filtering methods showed that for most subjects $F1$ was higher in modal than in falsetto register. Possibly this was a consequence of the widening of the oral cavity mentioned above. Using a different method, broadband acoustic excitation of singers' vocal tracts, Henrich *et al*. (2008) made similar observations. Hence, it seems reasonable to conclude that this is a typical difference between these registers, at least for the vowel /a/.

V. CONCLUSIONS

In this investigation we analyzed vocal tract shape, area functions, and formant frequencies in ten highly experienced operatic tenors. The two lowest formant frequencies derived from the area functions agreed with those derived from inverse filtering. We found that the vocal tract shape of the vowel /a/ differed between the two registers, the oral cavity being wider in modal. Furthermore, $F1$ was higher in modal register than in falsetto.

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