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Comparison of laryngoscopic, glottal and vibratory parameters among Estill qualities – Case study

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ABSTRACT

Estill Voice Training (EVT) is an effective educational system for developing and controlling distinct voice qualities used in contemporary commercial singing. EVT teaches six vocal qualities that differ at 13 levels. This study aims to investigate whether the distinct vocal qualities taught by EVT can be systematically differentiated based on laryngoscopic observations and vocal fold oscillation parameters. To investigate the differences in six EVT qualities, laryngeal dimensions and glottal area waveform parameters were measured in a single female subject who performed it in one-octave scale. Glottis Analysis Tools (GAT) were used to measure these parameters and phonovibrograms were obtained from the analysis. The resulting data were subjected to factor analysis to identify the systematic differences between EVT qualities. High-speed videolaryngoscopy analysis revealed a significant influence of vocal qualities on vocal fold oscillations. The factor analysis of the data identified three factors based on laryngeal dimension and four factors derived from GAT parameters. The first GAT factor was influenced by posterior adduction and distinguished belt quality from other qualities, suggesting a significant influence of the aryepiglottic sphincter. The second GAT factor contained parameters derived from glottal length and amplitude, suggesting a relationship not only with vocal registers but also with laryngeal height. The third GAT factor was best related to body-cover figure and phonation type (membranous medialization), while the fourth GAT factor was related to the amplitude-length-ratio. These findings suggest that vocal fold oscillations can be used to distinguish between Estill voice qualities.

1. Introduction

Contemporary singing performances require versatility and the ability to sing different styles or genres [1] , resulting in a shift towards more comprehensive approaches to teaching singing. One such approach is Estill Voice Training (EVT) [2–3] based on the work of Jo Estill, which has been published as the Estill Voice Model (EVM) [4]. This model has been further developed and includes a certification process with three levels: Estill Figure Proficiency (EFP), Estill Master Teacher (EMT), and Estill Mentor and Course Instructor (EMCI) [5].

Jo Estill's research began in the 1970s and led to the identification of four basic voice qualities (speech, cry, twang, and ringing opera), along with differences in their perceptual, spectral, physiological, and glottal flow pulse properties [6]. This work opened up new avenues for research into the physiological and acoustic properties of these qualities, including the role of the aryepiglottic constriction in producing the voice qualities of twang, belt and opera [7]. Further research led to the identification of five basic figures were described based on accepted voice pedagogy practices: three endolaryngeal sphincters (vocal folds, false vocal folds and aryepiglottic sphincter), and the position of the laryngeal and velopharyngeal opening. [8].

The EVM has evolved over time to include 13 mandatory functional areas for voice production, known as "figures." These figures are used to control various aspects of vocal production at the laryngeal and vocal tract levels. At the laryngeal level, the following figures are employed: onset/off-set, false vocal folds, body-cover, thyroid cartilage, cricoid cartilage, and aryepiglottic sphincter. Additionally, the configuration of the vocal tract is managed at six different levels, including laryngeal height, tongue position, velum position, jaw, and lips. Support is differentiated into two categories: head and neck, and torso [2] . Based on this framework, the EVT method identifies six fundamental vocal qualities [3], namely speech, falsetto, sob, twang, belt, and opera (see Table 1). Unlike registers, the EVT qualities can be produced consistently across the entire vocal range. For a comprehensive description of

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Table 1
Definition of basic Estill qualities based on the setting of 13 compulsory figures [4].

Compulsory Figure	Vocal folds - onset			False vocal folds			Body-cover				Thyroid		Cricoid		Aryepiglottic spincter		Larynx - hight		
Option	glottal	aspirate	smooth	constrict	mid	retract	slack	thick	thin	stiff	vertical	tilt	vertical	tilt	wide	narrow	low	mid	high
Speech	X				X			X			X		X		X			X	
Falsetto		X			X					X	X		X		X			X	
Sob			X			X			X			X	X		X		X		
Twang			X			X			X			X	X			X			X
Opera			X			X		X	X			X	X			X	X		
Belt	X	X	X			X		X			X			X		X			X

Compulsory Figure	Tongue				Velum			Jaw				Lips			Head & Neck		Torso	
Option	low	mid	high	compress	low	mid	hihg	forward	mid	back	drop	protrude	mid	spread	relax	anchor	relax	anchor
Speech		X				X			X				X		X		X	
Falsetto		X				X			X				X		X		X	
Sob			X				X		X				X			X		X
Twang			X				X		X				X		X		X	
Opera			X	X			X		X				X			X		X
Belt			X				X		X				X			X		X

the EVM method, please refer to Colton and Estill (1981) [6] and Steinhauer et al. (2017) [4].

Although the EVM has undergone significant development since its inception, research on the effectiveness of Estill Voice Training is still ongoing. A study by Fantini et al. (2017) found that singers with the EFP certification demonstrated better voice quality control than conventionally trained contemporary commercial singers [9]. Specifically, they were better able to control sound perturbation and spectral energy distribution during singing. Another study [10] found that a systematic manipulation of three of the Estill figures (false vocal fold constriction, laryngeal height and thin and thick conditions of the body-cover) resulted in independent acoustic effects. In a study of speech-language pathology students, slack, thick, thin, and stiff conditions of the body-cover (similar to vibration mechanisms) were objectively identified using sound pressure level (SPL), subglottal pressure, glottal airflow, and perturbation measures. However, contact quotient (CQ) values from electroglottography (EGG) did not distinguish among these voice conditions [11]. Furthermore, the EVM is recognized as an effective tool for the functional assessment of voice disorders because it applies anatomy and physiology (i.e., figures with conditions) to voice qualities, making it the only evidence-based framework of its kind [12].

EVM has not only contributed to the development of Estill Voice Training but has also influenced the creation of other modern schools of singing, such as the Complete Vocal Technique (CVT) [13–14]. In contrast to EVM, CVT focuses on three overarching principles: breath support, necessary twang, and the avoidance of jaw protrusion and lip tightening. CVT categorizes voice production into four basic modes (neutral, curbing, overdrive, edge [previously described as belting]), with the option to incorporate a metallic quality and perceptual characteristics to the voice. In addition to the basic principles and four vocal modes, CVT separately describes vocal effects (distortion, vocal breaks, air, vibrato, and ornamentation) as distinct components of voice production and sound color (darker-lighter continuum). For instance, the production of the rough vocal effect requires a specific supraglottic configuration to be produced safely [15]. Previous research has indicated that when performed using the correct technique for controlling the source, filter, and supraglottic vibrations, the use of the rough vocal effect according to the CVT method does not appear to pose an increased risk to vocal health [16]. In CVT, the vocal tract is divided into six levels, which are: the vocal fold level, ventricular folds, aryepiglottic folds, piriform fossa and posterior pharyngeal wall of the hypopharynx, soft palate, uvula, back wall of the throat (oropharynx), and the back of the tongue, and the oral and nasal cavity [17]. This approach provides a detailed understanding of the vocal anatomy and allows for precise targeting of specific areas to achieve the desired vocal effects. Independent research has also been conducted on the sound color of the voice, which is controlled by the size and configuration of the larynx and vocal tract [18], or the effect of adding air to the voice [19].

The Universal Voice System (UVS) is another pedagogical approach to voice training. It is built upon four foundational pillars: posture, breath, vocal cords, and sound space. UVS also identifies eight properties of sound including vibration, pitch, aspiration, loudness, adduction, vibrato, timbre, and nasality. Within the UVS framework, four distinct vocal qualities are defined: speech, belting, whisper, and classical [20].

The EVM, CVT and UVS are all pedagogical approaches that provide tools and techniques to singers for improving their vocal production. All three approaches share some similarities, such as a focus on proper breath management, posture, and vocal health. They also all acknowledge the importance of controlling aspects such as pitch, loudness, and timbre to achieve the desired sound. However, there are also differences among them. For example, while CVT emphasizes four basic vocal modes, UVS distinguishes four distinct qualities of sound, and EVM employs six voice qualities. UVS places significant importance on the sound space, while EVM focuses on the manipulation of various vocal structures. Despite these differences, all three approaches provide a systematic way of understanding and improving the voice, and singers may benefit from exploring each system to find the one that best suits their individual needs.

Comparing individual singing styles and genres is an important aspect of vocological research. Studies have primarily examined the differences between contemporary commercial music (CCM) and classical or opera styles in terms of subglottal pressure [21], glottal flow [22–23], laryngeal and vocal tract configurations [24], formant positioning [25], and resonance strategies [26]. Perceptual evaluation and radiation have also been found to differ between these styles. [27–30]. The effects of source filter interaction have also been investigated in the context of different singing styles [31]. These studies have shown that vocal technique can have a significant impact on the resulting quality of the sound, highlighting the importance of understanding the differences and similarities between different styles of singing. One of the key elements compared between singing styles was the oscillatory pattern of the vocal folds. Studies comparing different singing styles have used various methods to analyze vocal fold oscillatory patterns, including electroglottography [32] and glottal flow [33]. These methods have been used to compare phonation types [34], which range from hyperfunctional/pressed to hypofunctional/breathy phonation, with opera singing often being compared to flow phonation [35]. In contrast, speech is considered a neutral type. Recent research has identified new phonation types, such as firm [36] and hard [37], which have been observed in non-classical singing styles and are starting to be studied in greater detail.

High-speed imaging has proven to be a valuable tool in vocal research, especially in the investigation of register transitions [38–42]. It has also been used to evaluate the effects of vocal fatigue on glottis parameters [43] and vocal onset [44]. However, studies that focus on comparing different vocal qualities [45] and styles [46] are relatively rare, as most studies concentrate on describing supraglottic activity.

In a previous study conducted by our team [47], we compared various factors related to laryngoscopy, acoustics, and glottal characteristics among seven figures and six qualities produced in two pitches by a singer certified in EVT. Our findings revealed that laryngoscopic and glottal measurements could serve as a reliable basis for differentiating vocal qualities systematically. Based on these results, our current study aims to conduct more detailed measurements of EVT qualities within a one octave range. The objective of this research is to examine whether there are systematic differences between these qualities in terms of laryngoscopic observations and vocal fold oscillation parameters.

2. Methods

A single female subject (46 y.o.) with a Certificate of Estill Master Trainer in EVT participated in the study. Data were collected using synchronized acoustic and electrogottographic (EGG) signals (Laryngograph D200) and high-speed videolaryngoscopy (HSV, Phantom V611 VisionResearch, New Jersey, USA) with a 90° rigid laryngoscope (Olympus) at a frame rate of 8000 fps.

Fig. 1 shows the schematic of the equipment used in the experiment and Fig. 2 shows the flow diagram.

To improve the visibility of the larynx, two Olympus CLV-S45 (Olympus Corporation, Tokyo, Japan) light sources (300 W) were utilized to illuminate the vocal folds. A custom-made light adaptor was created and attached to the laryngoscope, parallel to it, to incorporate the second light source. The laryngoscopic examination was conducted by the participant herself, since the camera was mounted on a tripod.

The subject performed a total of six fundamental Estill qualities (speech, falsetto, sob, oral twang, belt, and opera). The qualities were produced in both ascending and descending scales from A3 to A4 at middle dynamics (mf) that are characteristic of each quality.

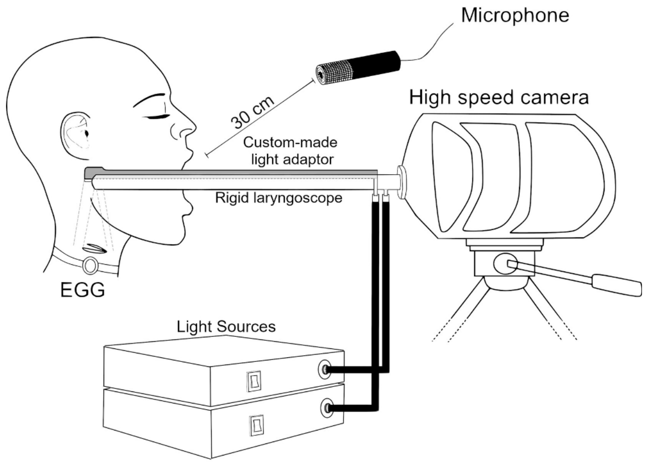

Fig. 1. Experimental setup.

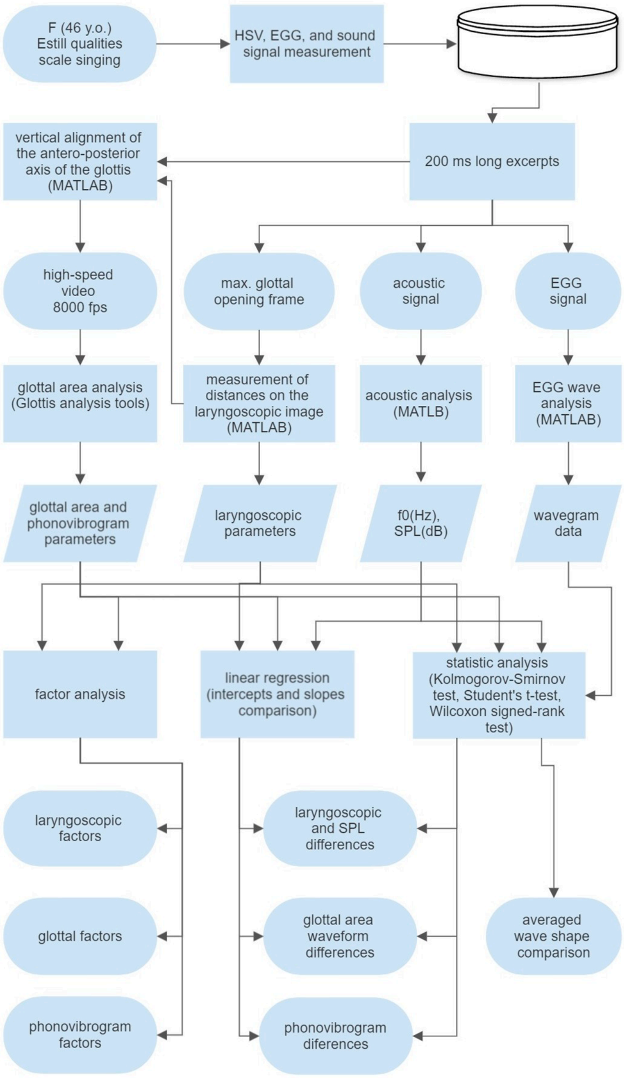

Fig. 2. Analysis procedure diagram.

The recording was primarily performed using the high-speed camera's slow mode (10 fps), and whenever a suitable phonation was identified (also allowing for a complete view of the glottis), one of the experimenters triggered the high-speed (8000 fps) sequence of 0.2 s. This method enabled up to 19 high-speed sequences per recording (16 GB of memory), providing sufficient data for further analysis. Out of the 173 recorded phonations for the 6 qualities, 147 were selected for analysis, with exclusion criteria being the inability to visualize the entire glottis, unsteady phonation (primarily during the vocal offset at the end of the phonation), and image blurring.

To analyze the laryngeal parameters, the images with the largest glottis opening from the middle part of the high-speed sequence were selected (see Fig. 3). The following parameters, selected on the basis of previous studies [43,48–52], were measured: the length of the membranous portion of the glottis (between the anterior commissure and the midpoint between the endpoint of the vocal processes), the A-P length (distance between the anterior and posterior commissures), the maximum amplitude of the vocal fold opening, the distance between the vocal processes, the maximum width between the false vocal folds, and the width between the false vocal folds perpendicular to the midpoint of the membranous portion.

Before conducting the HSV analysis, the antero-posterior axis of the glottis was aligned vertically. Subsequently, subsets of the HSV files were analyzed using the Glottis Analysis Tools (GAT, University Hospital Erlangen, Erlangen, Germany). This tool enabled the evaluation of various laryngeal parameters such as frequency, perturbation, amplitude, period, energy, noise, mechanical, glottal area waveform, and symmetry. Additionally, acoustical parameters such as fundamental frequency and sound pressure level at a distance of 30 cm were calculated from the synchronously recorded sound signal.

To compare the measured parameters among the different qualities, we employed statistical analysis. The statistical analyses were conducted mainly using MATLAB software. Normality was checked using the Kolmogorov-Smirnov test. The middle values for all pairs of qualities were compared using either Student's *t*-test (for normally distributed data) or the Wilcoxon signed-rank test (for non-normally distributed data). In the post hoc test, the Bonferroni correction was applied for multiple comparisons.

An additional analysis was conducted to investigate the effect of voice pitch on the measured parameters. A linear regression model was fitted using the MATLAB fitlm function, where pitch and quality were predictor variables and the measured parameter was the response variable. The intercepts of the pitch-dependent parameters between two qualities were compared using the model. To compare the slopes of the regression lines, an interaction model was used, where quality was treated as a categorical variable.

The Phonovibrogram (PVG) results obtained from the GAT analysis were used to calculate the vibration amplitude maxima and minima of the vocal folds opening along the anteroposterior axis, as described in Lohscheller et al. (2013). [53] To evaluate the CQ and SQ values along the anteroposterior axis of the vocal folds, a similar approach was employed.

Finally, a factor analysis using varimax raw method in STATISTICA 6.0 was conducted to identify the main components of variability in the laryngeal measurements, GAT parameters, averaged glottal area waveform, relative vibration amplitudes at maximal opening and maximal closure, OQ and SQ, and EGG wavegram averaged pulses.

3. Results

3.1. Laryngoscopic parameters

Fig. 4 illustrates the correlation between ***sound pressure level (SPL)*** and laryngoscopic measurements, as well as changes in pitch. The left side of the graph displays the regression analysis and the statistical comparison between different qualities. On the right side of the graph, the data distributions and mean value comparisons between qualities are presented.

To provide further clarification, the results of the sound pressure level (SPL) measurements (@ 30 cm) are explained in more detail. High-speed recordings were obtained for each pitch produced during a singing scale task. For each high-speed excerpt, the mean SPL value was calculated and plotted as a function of pitch, with different qualities indicated by varying colors and shapes.

The results showed significant linear relationships ($p < 0.05/6$) between SPL and pitch for the falsetto, sob, and opera qualities. Trend lines for each quality are color-coded and shown as thick solid lines.

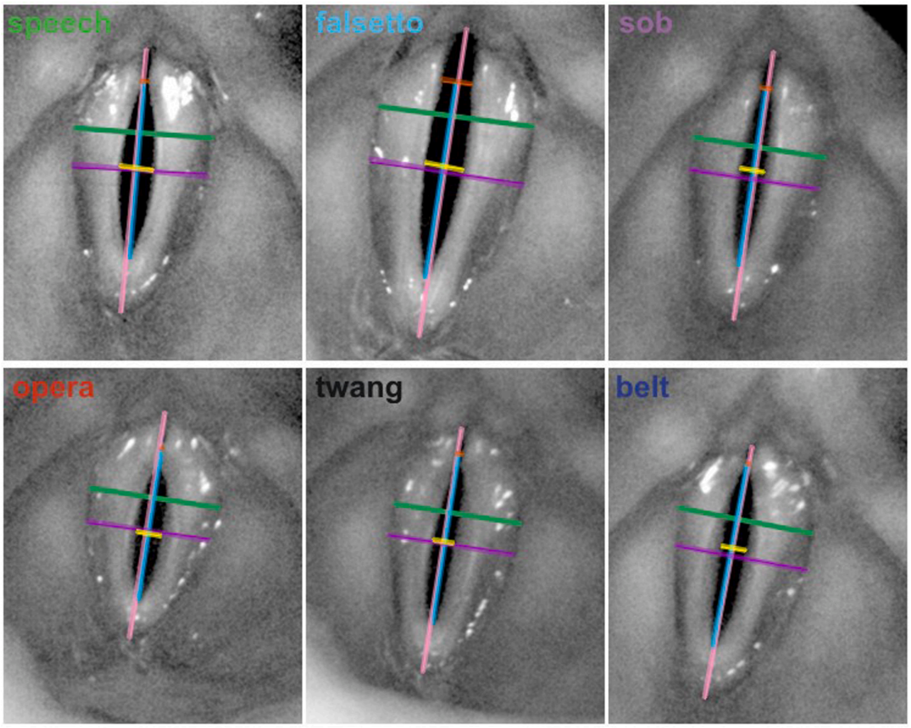

Fig. 3. Illustration of the measured distances of the laryngoscopic images during maximum glottis opening. Laryngeal parameters: membranous glottal length (light blue line), antero-posterior length of vocal folds (pink line), maximal glottal opening (yellow), maximum width of false vocal folds (green), false vocal folds width in the middle of the membranous part of the vocal folds (purple), and vocal processes width (red).

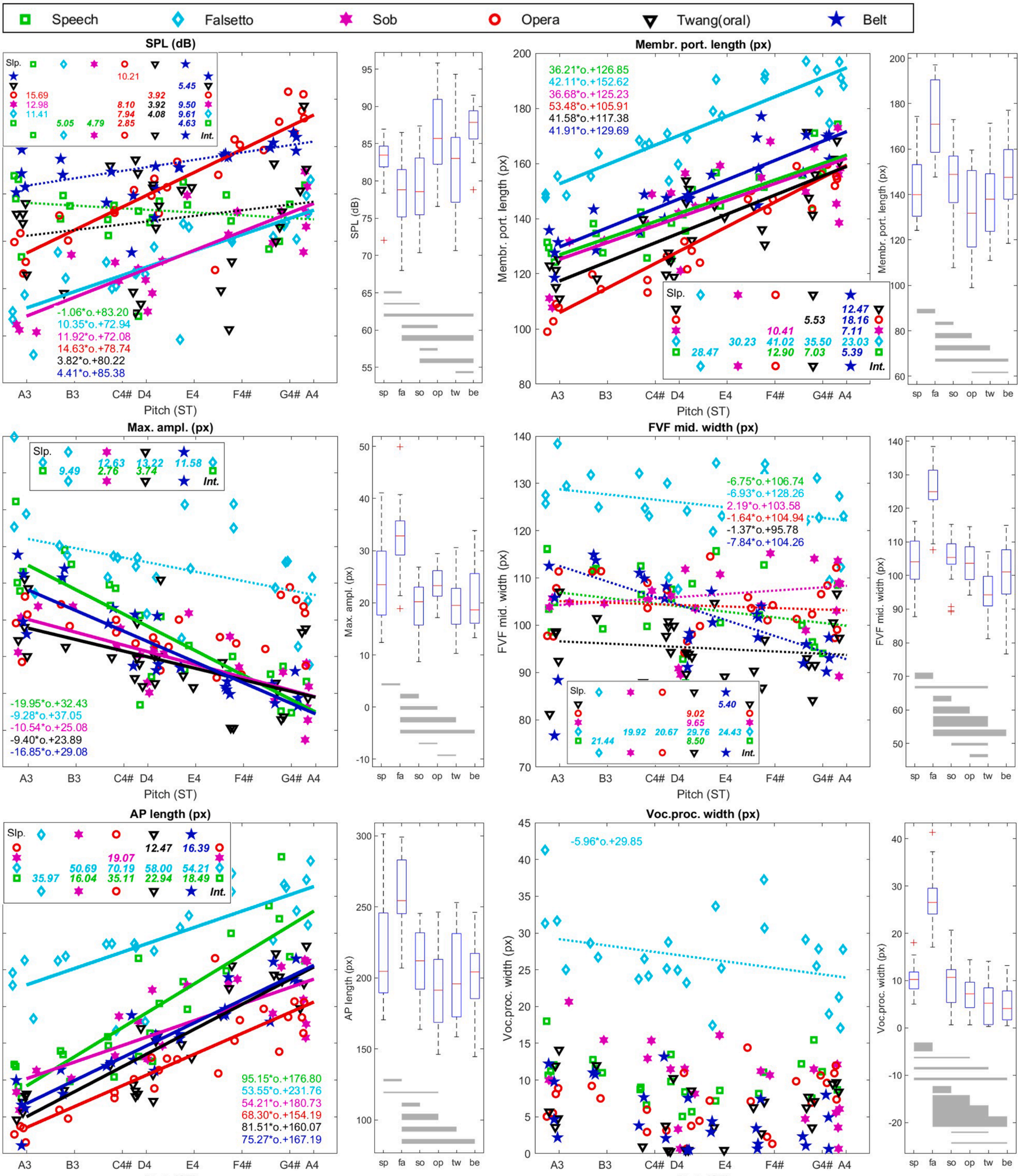

Fig. 4. The left parts of the graphs show the relationship between the pitch and measured parameters (SPL and distances obtained from the laryngoscopic images). A solid line represents a significant linear relationship between pitch and measured variable (only differences with $p < 0.05/6$ (Bonferonni correction) are shown), while the dotted line indicates a linear relationship found based on the robustfit function. The equations for the regression lines are shown with the slope related to one octave and the intercept recalculated for the pitch A3 (220 Hz). Pairwise comparisons of the differences in the slope of the regression lines and intercept are shown in the rectangular box in the graphs (only differences with $p < 0.05/15$ (Bonferonni correction) are shown). The boxplot and whiskers right to the graphs show the distribution of the data for each quality. Statistically significant comparisons of mean values are shown in the bottom part of the graphs as horizontal lines between qualities whose level of statistical significance was $p < 0.05/15$ (Bonferroni correction). The levels of significance are represented by the thickness of the horizontal lines. The labels in the boxplot's x-axis refer to: speech (sp), falsetto (fa), sob (so), opera (op), twang (tw) and belt (be).

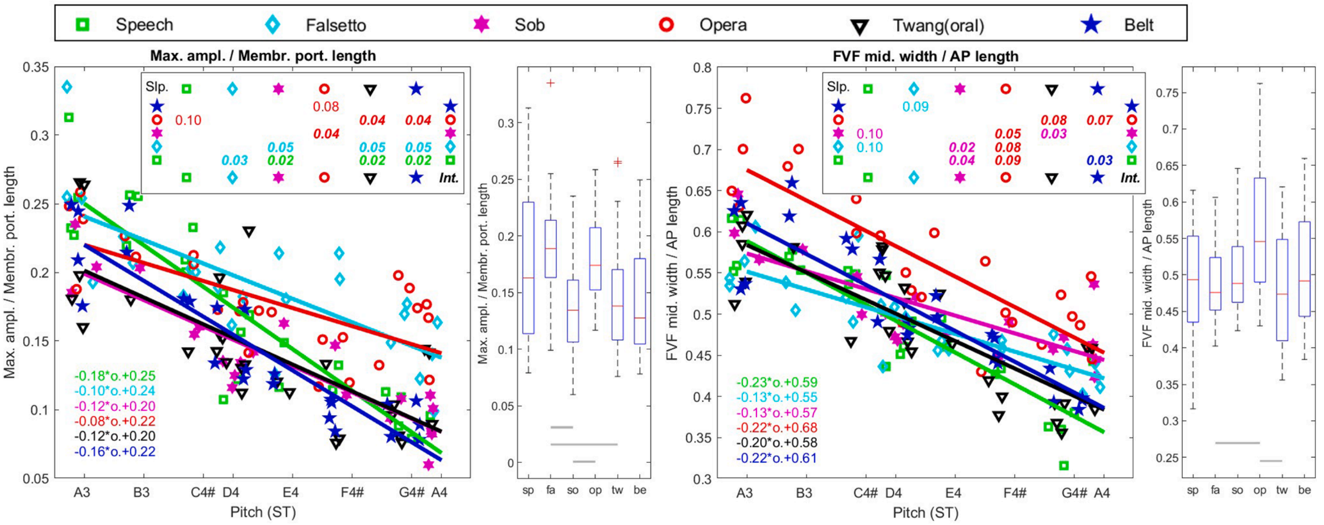

Fig. 4. (*continued*).

The regression analyses showed no significant linear relationship between SPL and pitch for the belt, twang, and speech qualities. However, using a more robust estimation of correlation (i.e., using robustfit function), significant levels were reached, indicating that only a small number of points were outside the predicted linear relationship between SPL and pitch. The robust trend lines for these qualities are shown as thin dotted lines in Fig. 4. The regression equations for all qualities that showed significant results for the regression or robust linear relationships are provided in the figure. For instance, for falsetto, the equation SPL = 10.35 * octave +72.94 was produced, where the coefficient 10.35 denotes the slope of the line segment and indicates how many dB the SPL changes when the pitch increases by one octave. The constant +72.94 is the intercept of the regression line and indicates what the predicted SPL value is at pitch A3 (220 Hz). Similarly, for the speech quality, the robust equation is SPL = −1.06 * octave +83.2, indicating that the straight line estimate of linear SPL with respect to pitch decreases by 1.06 dB per octave, and at the A3 pitch, the predicted SPL value is 83.2 dB.

The boxes within the graphs display comparison tables for the slopes and intercepts values, respectively. In these boxes, the upper left part of the tables show the difference between slopes while the bottom right part shows the difference between intercepts. Data is only presented if the results are significant ($p < 0.05/15$). The significant results are indicated in the tables by the color of the quality with the higher intercept and steeper slope. The first row of the comparison tables indicates that the opera quality (red circle) had a significantly steeper slope compared to the belt (blue five-pointed star) by 10.21, hence the slope difference is written in red. Another example is the value of 4.63 (in blue, bold, italic) in the bottom right corner of the table, which indicates that the belt quality had a higher intercept compared to speech. The entire right-hand column of the tables displays blue values, except for the comparison with opera, which suggests that the belt quality had higher intercept values than other qualities (speech, falsetto, sob, and twang) and, therefore, higher overall SPL values. The boxplots to the right of the regression graphs display the distribution of data for each quality, with each quality represented by individual columns in the boxplot. The horizontal gray lines below the boxplots indicate the pair-comparisons between qualities, and the thickness of the line corresponds to the statistical significance of the means comparison (i.e., a thicker line indicates a more significant difference between the qualities).

The comparison of SPL values showed that speech had significantly higher SPL values compared to falsetto and sob, but produced lower SPL values compared to belt. Falsetto quality had lower SPL values compared to speech, opera, and belt. Sob had lower SPL values than opera and belt, while belt showed higher SPL values than twang.

The length of the membranous part of the glottis displayed a significant positive linear correlation with pitch for all voice qualities. The statistical analysis of mean differences showed that falsetto had the highest value compared to all other qualities, while belt showed significantly higher value when compared to opera. However, when examining the linear regressions, differences in intercept were observed among all qualities except for the sob-speech and twang-sob pairs. This suggests that the relationship between glottis length and pitch varies among the different voice qualities, and that the intercept values may play a crucial role in distinguishing between them.

Measurements of ***the maximum amplitude of glottal opening*** revealed a negative correlation with pitch for all qualities, except opera. The boxplots showed significantly higher mean values for falsetto when compared to the other qualities. Significant differences were also found for the sob-opera and opera-twang pairs. The intercepts of the linear regressions differed among the qualities, with falsetto having the highest values in the dataset followed by speech. The comparison of intercepts also indicated that speech was significantly different from sob and twang.

The width of the false vocal folds at the mid-length of the membranous part of the vocal folds (FVF mid. width), demonstrated a linear relationship with pitch for all qualities. However, this relationship was only shown using the robustfit estimation (indicated by dotted lines). Although the slopes of the relationship appeared to vary significantly, this difference was not confirmed by statistical analysis. The most significant differences are in the intercepts, but these can also be assessed by the comparison of the means. Additionally, the falsetto quality produced the highest FVF mid. width value, while the twang quality produced the lowest value. The mean differences were also noticeable in the speech-twang, sob-twang, and opera-twang pairs.

Across all qualities, a significant positive correlation was found between ***the antero-posterior length*** of the visible part of the vocal folds and pitch. Falsetto produced the highest values, setting it apart from the other qualities. Furthermore, a significant difference in mean was also observed between speech and opera. While comparing linear regressions, the differences in the intercept values were more apparent. Opera produced the lowest values, speech produced middle values, and falsetto produced the highest values. The values for sob, twang, and belt singing were between those for opera and speech, but were not statistically different from each other.

The analysis of ***vocal process width*** revealed the weakest correlation with pitch across all of our data. We observed a negative linear trend for falsetto alone, based on the robust fit, and thus we did not compare linear regression constants. However, when we compared the means across all groups, we found a significant difference between the speech-opera, speech-twang, and speech-belt pairs, as well as large statistical significant differences between falsetto and other qualities. We also observed that sob produced significant higher values than twang and belt.

The ratio of the maximum amplitude to the length of the membranous portion of the vocal folds exhibited negative linear relationships with pitch across all vocal qualities. When comparing mean values across all groups, we found significant differences between the falsetto-sob, falsetto-twang, and sob-opera pairs. In particular, the slope was significantly higher for opera relative to belt and speech. We also observed several differences in the intercept, with falsetto producing the highest values, speech and opera exhibiting intermediate values, and twang, sob, and belt showing the lowest values.

The ratio of the width of the false vocal folds (FVF) at the middle of the membranous portion of the vocal folds to the anterior-posterior (A-P) length of the vocal folds exhibited a negative linear relationship with pitch across all vocal qualities. Notably, the only significant differences in this relationship were observed between the falsetto-opera and opera-twang pairs. Regarding the intercepts of the linear regression, the highest values were found for opera, followed by sob and belt, and the lowest values were seen for speech and twang. Furthermore, significant differences were found between falsetto and speech, with higher slope for falsetto.

3.2. Factor analysis of laryngoscopic parameters

Table 2 presents the results of the factor analysis of laryngoscopic parameters across all vocal qualities. The measured parameters can be grouped into three factors, which collectively account for 94.56% of the variability in the data. The first factor, denoted as ***Factor: 1 (amplitude)***, consists of two variables: the maximum amplitude of glottal opening and the width between vocal processes. As such, it is primarily related to vocal fold vibration amplitude. The second factor, ***Factor: 2 (glottal length)***, comprises the membranous and anterior-posterior lengths of the vocal folds, and is thus mainly associated with glottal length. Lastly, the third factor, ***Factor: 3 (supraglottal)***, is composed of the width parameters of the false vocal folds and is related to supraglottal configuration.

The results of the factor analysis of laryngoscopic parameters are displayed in Fig. 5. Overall, the analysis was able to effectively differentiate most vocal qualities based on three factors. The first factor, denoted as ***Factor: 1 (amplitude)***, distinguishes falsetto from all other qualities, with falsetto exhibiting the highest scores in this factor. The lower row of Fig. 5, which shows the linear regression analysis, further separates speech from sob and belt based on their intercepts. Similarly, the second factor, ***Factor: 2 (glottal length)***, separates falsetto (with the highest scores) from all other qualities, with the linear regression analysis revealing different slopes between speech and sob, and distinct intercept values among most qualities. Once again, the third factor, ***Factor: 3 (supraglottal)***, clearly distinguishes falsetto with the highest values from all other qualities. Additionally, it highlights differences between the sob-twang and opera-twang pairs. The linear regression analysis distinguishes belt and opera based on intercept only. Notably, the marked difference between falsetto and other qualities is evident in the boxplots, where significant overlap among the other qualities is observed.

Table 2
Results of the factor analysis of laryngoscopic parameters. Only coefficients whose factor loadings were greater than 0.7 are shown.

LAR Parameters - Factor analysis Par.	**Factor: 1 (amplitude)**		**Factor: 2 (glottal lenght)**		**Factor: 3 (supraglottal)**	
	Fa. Sc. Coeff	**Fa. Loadings**	**Fa. Sc. Coeff**	**Fa. Loadings**	**Fa. Sc. Coeff**	**Fa. Loadings**
Membr. port. length (px)			−0.20	0.92		
Max. ampl. (px)	0.92	0.89				
FVF max. width (px)					0.77	0.81
FVF mid. width (px)					0.97	0.86
AP length (px)			−0.24	0.94		
Voc.proc. width (px)	0.70	0.74				
% Total variance	*66.15*		*23.58*		*4.83*	
% Cumul. variance	***66.15***		***89.73***		***94.56***	

3.3. Glottal parameters (based on the GAT software)

The glottal parameters were analyzed using the Glottis Analysis Tools (GAT, University Hospital Erlangen, Erlangen, Germany), as shown in Fig. 6. Thirteen parameters were included in the factor analysis of the glottal parameters based on prior research, [47,54] including mechanical parameters (stiffness, peak closing velocity, peak acceleration), glottal area waveform parameters (open quotient, closing quotient, speed quotient, asymmetry quotient, glottis gap index, glottal area index), time periodicity, parameters derived from the glottal area waveform (maximum area declination rate, amplitude quotient), and amplitude-length ratio.

Differences in ***open quotient*** were mainly observed between speech and twang/belt, as revealed by the comparison of means. Falsetto demonstrated the highest values with a consistent value of 1 for all pitches and was found to differ significantly from opera, twang, and particularly belt. Sob was observed to be distinct from twang and belt, while opera was only distinct from belt. The linear regression analysis confirmed the global results, with a significant decreasing trend observed only for belt.

A linear dependence on pitch was observed for the ***closing quotient*** based on the robustfit analysis. Differences were also noted in intercept, with a decreasing order from falsetto to belt, followed by sob and speech. Only falsetto demonstrated an upward trend. A global comparison of mean values confirmed differences in almost all qualities, except for the speech-opera and twang-belt pairs.

A linear relationship with pitch was observed for ***speed quotient*** only for belt, while a significant relationship for opera and falsetto was found using robustfit. The lowest intercept value was observed in falsetto. The overall pattern showed that falsetto had the lowest values, but significant differences were also observed among the pairs, including speech-sob, speech-opera, sob-twang, and sob-belt.

The maximum area declination rate (MADR) showed a positive correlation with pitch for all qualities except for sob, which had the smallest values in this parameter, differing from the other qualities. Overall, speech, opera, and twang qualities were not distinguishable, but significant differences were observed among the other pairs.

Amplitude quotient showed a linear trend with pitch for all qualities with a decreasing trend. Linear trends differed between qualities, particularly regarding intercept, where falsetto had the highest value, followed by sob, opera/speech, which were indistinguishable, and finally twang/belt (also indistinguishable). Similar differences were shown in the comparison of means. The linear trend showed the greatest steepness for falsetto, which was distinguished from belt, twang and opera.

Stiffness was found to have a linear relationship with pitch for all qualities. The slope of the relationship was highest for belt, clearly distinguishing it from all other qualities. The intercept values differed

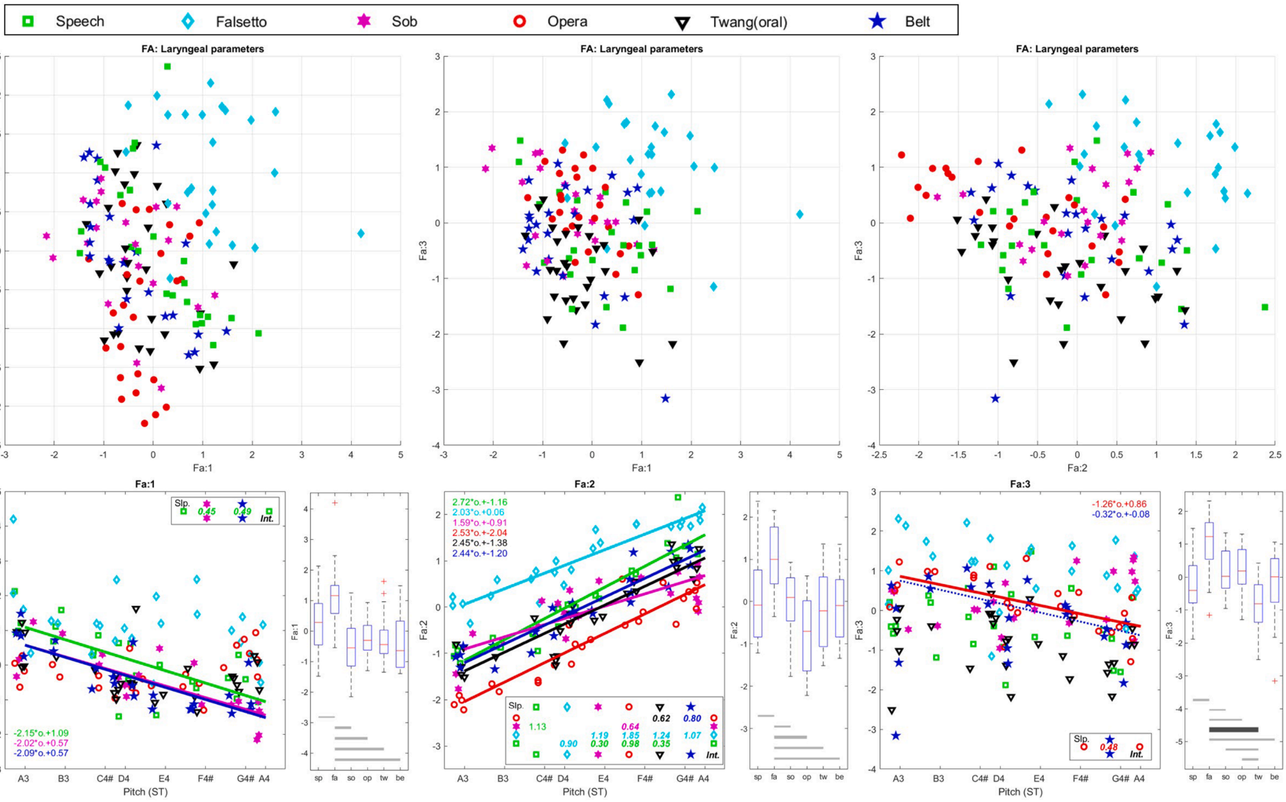

Fig. 5. Results of factor analysis of laryngoscopic parameters. The top row shows the distribution of factor scores. The bottom row shows the relationship between factors and qualities across the different pitches (left side) and the comparison of means (boxplot graphs on right side). Refer to the legend in Fig. 4 for a more detailed explanation.

among the qualities, with belt having the highest intercept, followed by twang and opera. Speech had a higher intercept value than falsetto and sob. With regards to differences in slope, belt had a significantly steeper slope than all other qualities, indicating that changes in stiffness were more pronounced in belt than in other qualities. The comparison of means indicated that falsetto was different from opera, twang, and belt, while sob was distinguishable from twang and belt.

Peak acceleration also exhibited a linear relationship with pitch for all qualities, allowing the distinction of falsetto, which had the highest values from all other qualities except opera. Falsetto had the highest intercept in the linear trend, which was significantly different from speech, sob, twang, and belt. Additionally, falsetto and opera had significantly steeper slopes than belt, twang, and sob, and speech and belt, respectively.

Amplitude-length ratio exhibited a regression dependence on pitch for belt, speech, and twang, and the robustfit estimates also showed this for falsetto, opera, and sob. The qualities differed in terms of the slope of the line, speech and belt had a steeper slope than the other qualities, indicating a greater decrease in this parameter with increasing pitch. The comparison of means showed differences between the speech-sob, falsetto-sob, falsetto-twang, sob-opera, and sob-belt pairs.

3.4. Factor analysis of glottal parameters

The results of the factor analysis, presented in Table 3, indicated that the GAT parameters could be described by four factors, which accounted for 89.88% of the total data variability. The first factor included open and closing quotients, which had a negative relationship with the glottal area index. The second factor included peak acceleration, peak closing velocity, and MADR. The third factor included speed quotient and asymmetry quotient, while the fourth factor was primarily saturated with amplitude-length ratio.

Fig. 7 displays the distribution of qualities in relation to each factor, where clear clusters are observed, distinguishing some of the qualities from one another. In the first factor, belt is situated opposite to falsetto and sob, while twang, opera, and speech gradually shift from one pole to the other. The second factor is relatively dispersed for all qualities, with falsetto at one end and sob at the other, although there is significant overlap in the middle. The third factor better distinguishes falsetto, sob, and speech from each other. All qualities overlap in the fourth factor.

Fig. 8 displays the correlation between the analyzed factor scores of GAT parameters and pitch for all qualities. The regression analysis confirmed a linear relationship between pitch and the ***first GAT factor*** only for belt and falsetto, which differed in the intercept. The comparison of mean values showed that falsetto was distinguishable from all qualities except sob. Additionally, it showed that speech was distinguishable from belt, sob was distinguishable from opera, twang was distinguishable from belt, and finally, opera was distinguishable from belt.

The second GAT factor also exhibited a linear relationship with pitch for all qualities. The comparison of means showed that sob had significantly lower scores than speech, falsetto, and belt. However, the comparison of linear regression coefficients revealed more differences between qualities. The slope of the line was highest for falsetto, which distinguished it from belt and speech. Meanwhile, the intercept decreased in the order from falsetto, through belt, speech, opera, and twang to sob.

The third GAT factor showed a linear dependence on pitch only for belt. The comparison of means distinguished speech from all qualities except twang. Falsetto differentiated from all qualities with the lowest values, and finally sob differentiated from twang and belt.

The fourth GAT factor exhibited a linear relationship with pitch for all qualities, except for opera. The comparison of means revealed that falsetto was distinguishable from sob and twang, and opera was

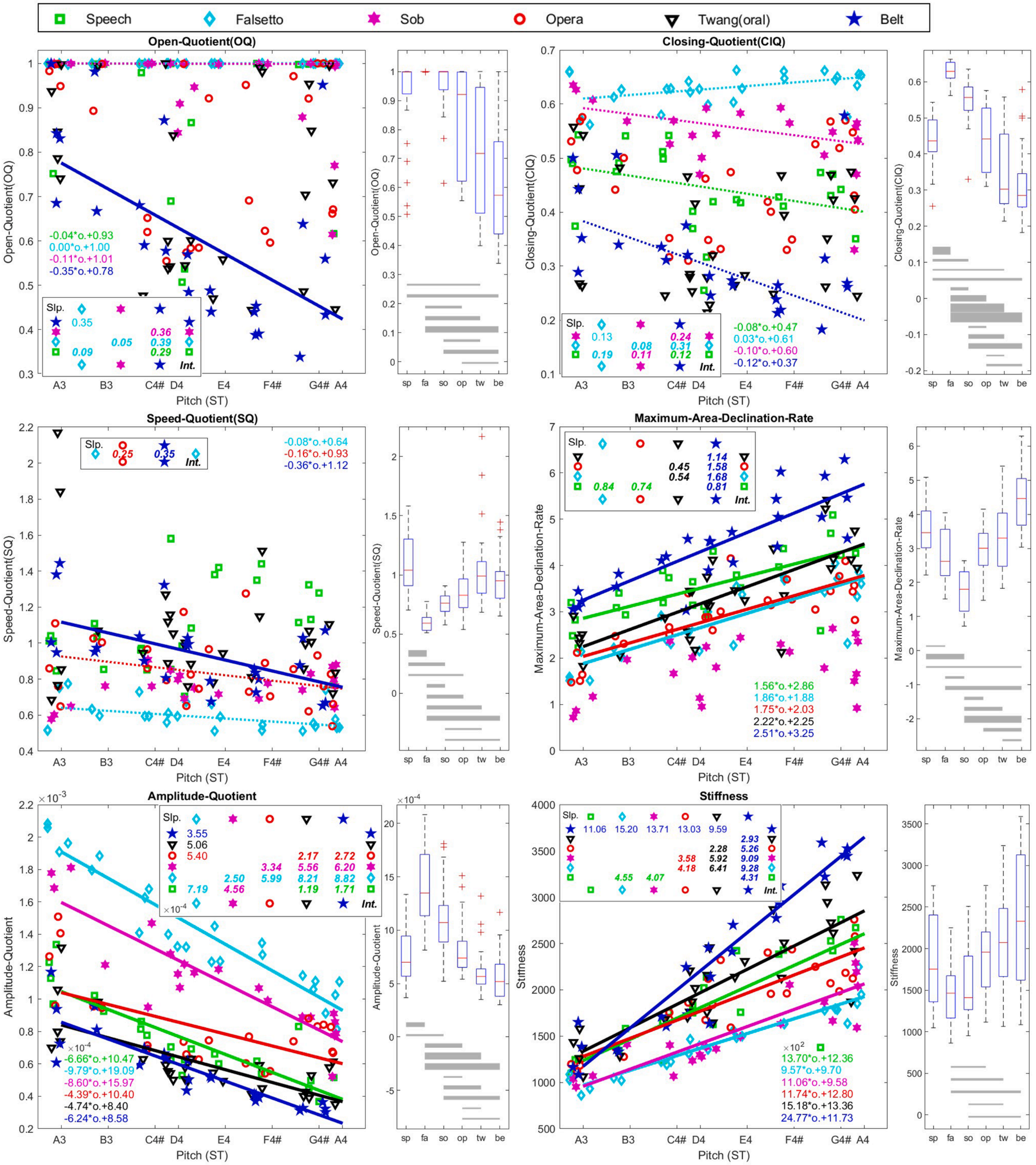

Fig. 6. Results of the glottal parameters analyzed using the GAT software. On the left side of the graphs is shown the relationship between factors and qualities across pitch. The tables inside the graphs show pairwise comparison of linear trends. The boxplots (on the right) show data distribution for each variable and mean / median comparison among qualities. For a more detailed explanation refer to the legend in Fig. 4.

distinguishable from sob. The linear regression analysis showed that belt had the highest slope, whereas the intercept decreased in the order of sob, twang, speech, belt, and finally falsetto.

Based on the process described by Lohscheller et al. (2013) the following parameters were obtained: normalized values of relative vibration amplitude along the glottal length (maximal opening phase and maximum closing phase), and open and speed quotients along the glottal long axis. [53] A factor analysis was conducted on these parameters, and the results are presented in the following section. However, as the details of the analysis are beyond the scope of this study, we refer the reader to the original work by Lohscheller et al. (2013) for further information.

The results of the factor analysis of the ***maximum opening phase and***

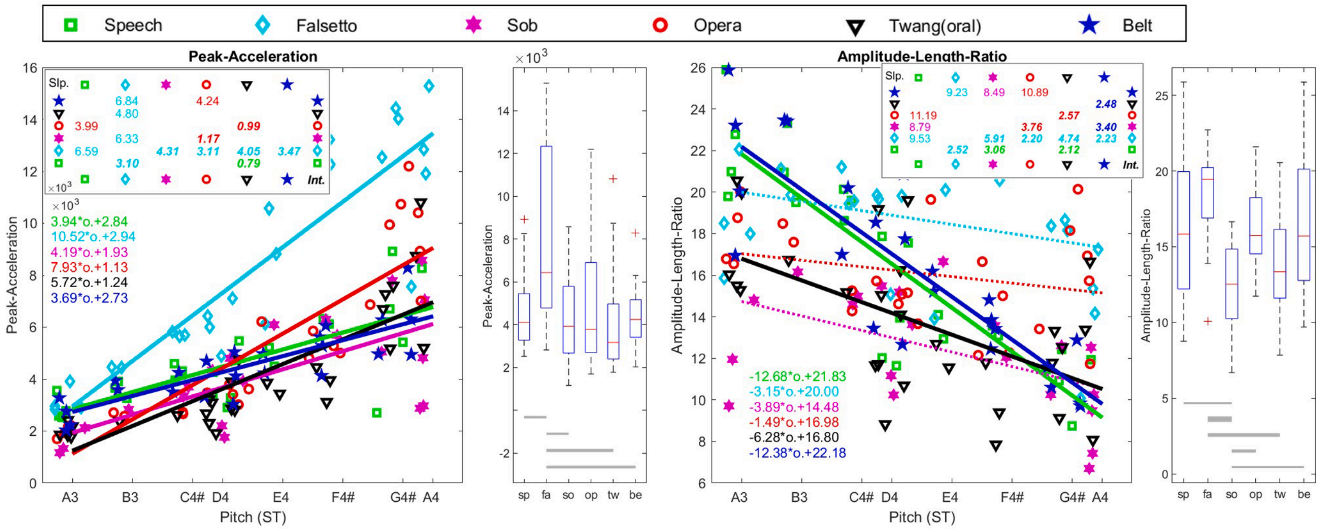

Fig. 6. (*continued*).

Table 3
Results of the factor analysis of the glottal parameters using the GAT software. Only coefficients whose factor loadings were greater than 0.7 are shown. Fa. Sc. Coeff - factor score coefficient. Fa. Loadings - factor loadings.

GAT parameters - Factor analysis	Factor: 1		Factor: 2		Factor: 3		Faactor: 4	
Par.	**Fa. Sc. Coeff**	**Fa. Loadings**	**Fa. Sc. Coeff**	**Fa. Loadings**	**Fa. Sc. Coeff**	**Fa. Loadings**	**Fa. Sc. Coeff**	**Fa. Loadings**
Open-Quotient (OQ)	0.28	0.98						
Closing-Quotient (ClQ)	0.21	0.90						
Speed-Quotient (SQ)					0.37	0.92		
Asymmetrie-Quotient (AsQ)					0.37	0.94		
Glottis-Gap-Index (GGI)								
Glottal-Area-Index (AC/OQ)	−0.26	−0.97						
Maximum-Area-Declination-Rate (MADR)			0.32	0.71				
Amplitude-Quotient (AmQ)								
Time-Periodicity (Per)								
Stiffness (St)								
Peak-Closing-Velocity (PCV)			0.36	0.89				
Peak-Acceleration (PAc)			0.36	0.92				
Amplitude-Length-Ratio (ALR)							−0.63	−0.89
% Total variance	*43.13*		*22.71*		*14.65*		*9.39*	
% Cumulative variance	***43.13***		***65.84***		***80.49***		***89.88***	

maximum closing phase along the glottal length are shown in Fig. 9, where the data was divided into four factors. The first factor contained a region between 40 and 70% of the glottis length at maximum opening phase, where only falsetto showed a linear trend with pitch. The comparison of means distinguished falsetto from speech, sob, and opera, and further distinguished sob from twang and belting. Belt could be distinguished from opera and speech. The second factor involved 0–50% of the glottis length during maximum closure, where no qualities could be distinguished and a linear trend with pitch was not detected. The third factor contained 50–90% of maximum vocal fold closure and was linearly correlated with pitch for speech and twang, while means comparison distinguished falsetto and sob from other qualities. The fourth factor contained 0–15% of the maximum opening phase and was linearly related to pitch in speech. The comparison of means distinguished falsetto from sob, twang, and belt, and distinguished speech from sob.

The measurements of open and speed quotients along the glottal long axis were subjected to factor analysis, resulting in four distinct factors as shown in Fig. 10. The first factor covered almost the entire length of the glottis for OQ and exhibited a linear dependence on pitch for speech, sob, twang, and belt qualities. It globally distinguished falsetto and sob from other qualities and found that opera differed from belt. The second factor included SQs from 10 to 70% along the glottal length, but no linear dependence on pitch was observed for any quality. It mainly distinguished twang from other qualities. The third factor represented only a small region of SQ around 90% of the glottis length and exhibited a linear dependence on pitch only for belt. It mainly distinguished speech from other qualities, except for sob, and also distinguished falsetto from belt.

4. Discussion

4.1. *Sound pressure level and laryngoscopic parameters*

Based on the results, the SPL analysis categorizes the qualities into three distinct groups. The quietest qualities are sob and falsetto. Twang and speech show similar mean SPL values, however, the SPL for speech decreases with increasing pitch, which is in line with Estill's description of working with qualities. [3] Twang exhibits the greatest dynamic range among all the qualities. The highest SPL values are produced by belt and opera, with opera showing a much greater dynamic range, increasing by up to 14 dB over the octave, compared to belt's 4.4 dB increase. The three qualities that involve aryepiglottic sphincter narrowing (opera, belt, and twang) were found to be the loudest in this study, which supports previous findings by Yanagisawa et al. (1989). [7]

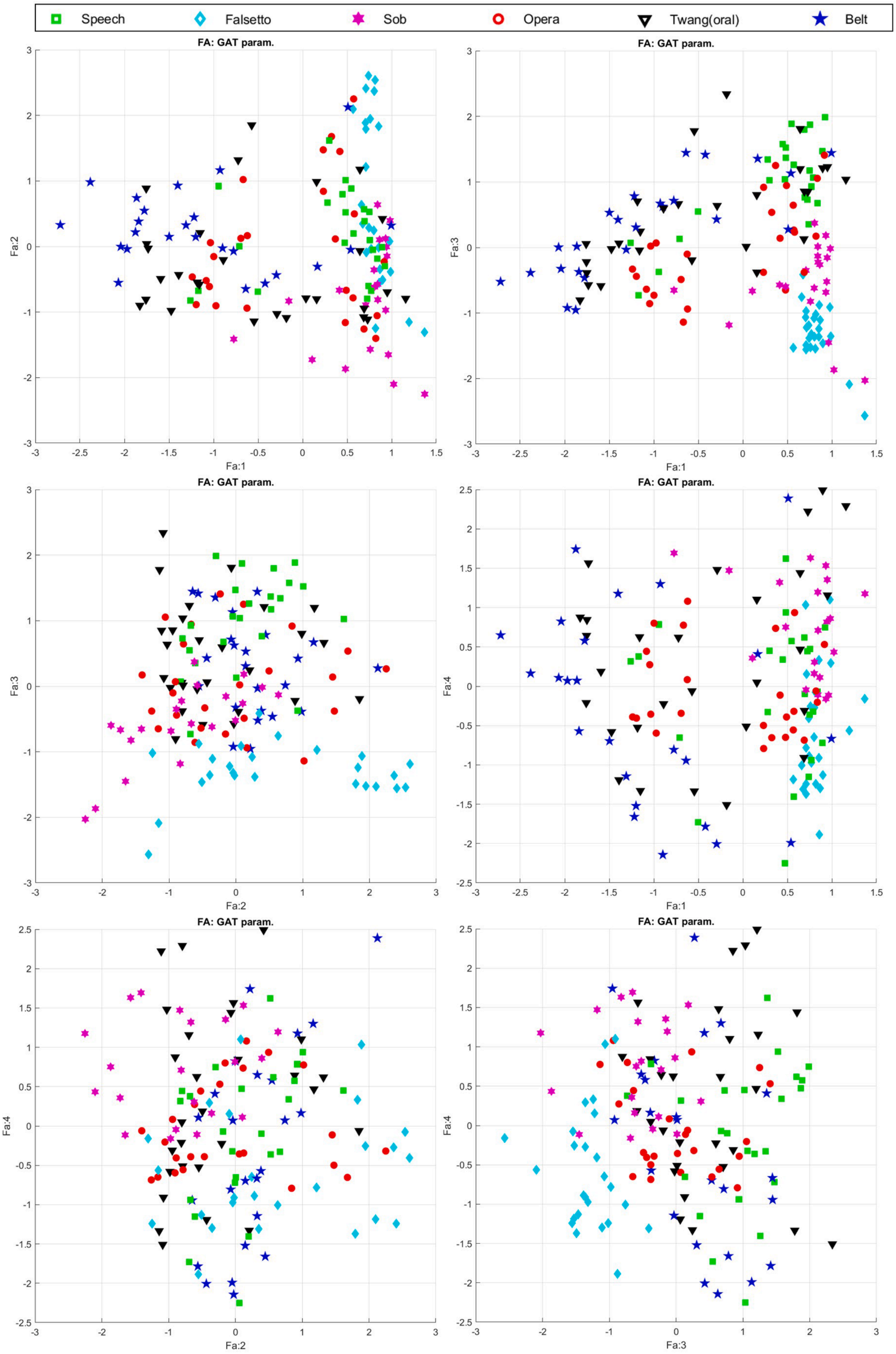

Fig. 7. Results of factor analysis of glottal analysis tool (GAT) parameters. Graphs show the distribution of factor scores.

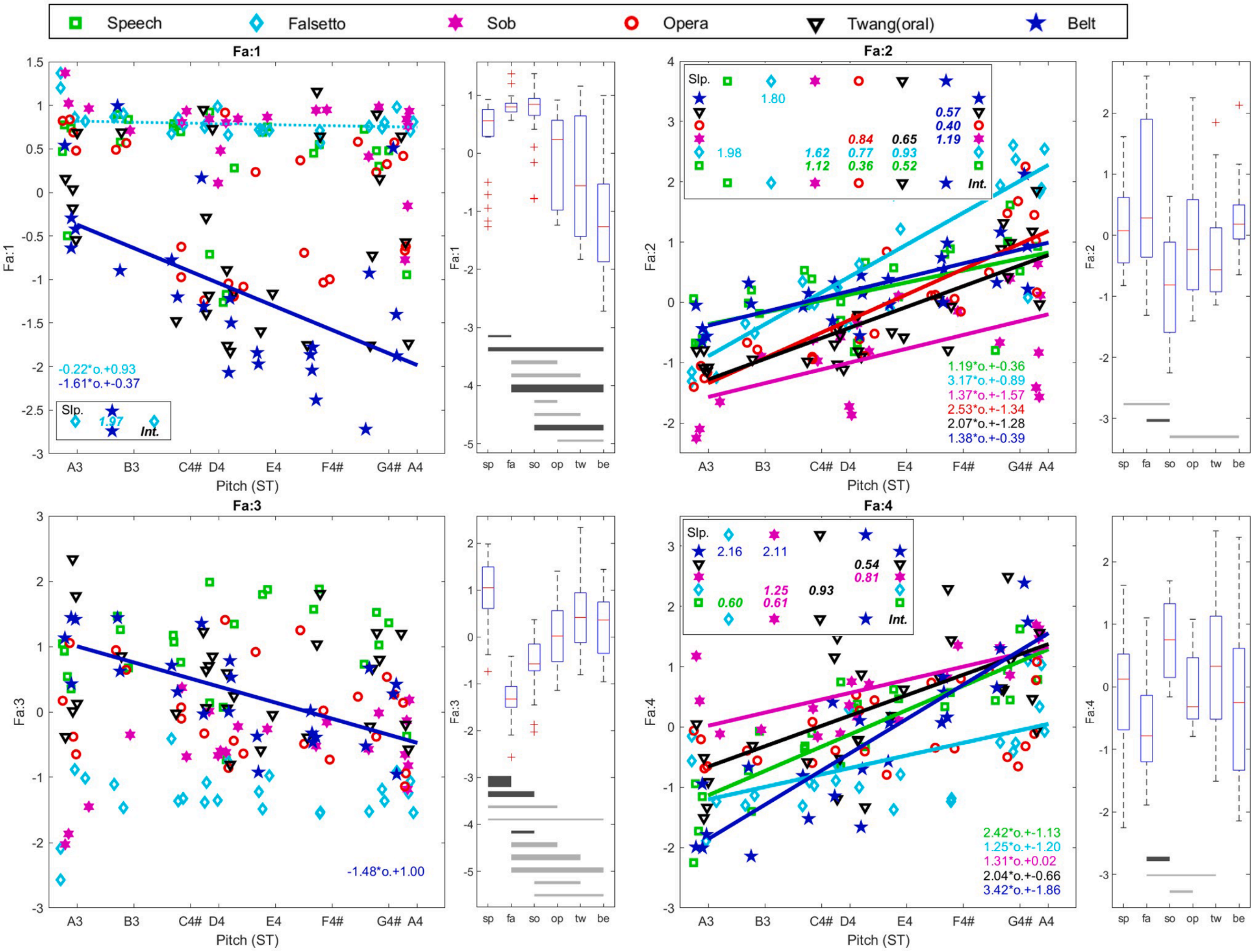

Fig. 8. Results (factor scores) of factor analysis of glottal analysis tool parameters. Left side of the graphs show the relationship of factor scores of each quality with pitch, tables inside the graphs show the comparison of linear trends. The right side boxplot graphs show mean / median values comparison of factor scores among qualities. A more detailed explanation is given in the caption to Fig. 5.

Significant correlations between SPL gain and rise in pitch were found for opera, sob and falsetto.

The results suggest that for falsetto, there may be a correlation between low SPL values and low adduction rates in the posterior glottis, specifically in the vocal processes area. This correlation has been supported by a minimum glottal opening from PVG analysis along glottal length. In contrast, sob showed slightly better adduction of the glottis with relatively small oscillation amplitude. Therefore, it is important to consider that the low SPL values in falsetto are mainly associated with low vocal fold contact and a high degree of breathiness, while in sob, the reduction in SPL is mainly due to a decrease in subglottal pressure. Based on these differences, it can be suggested that falsetto and sob are similar to breathy and flow phonation, respectively, as supported by previous studies [55–58].

Based on the laryngoscopic analysis, it can be observed that there is a strong correlation between voice pitch and most laryngoscopic parameters. In particular, the falsetto quality stands out as producing the highest values for parameters such as the length of the membranous part of the vocal folds, maximum amplitude, FVF width, and AP length. These differences were confirmed by the factor analysis of the laryngoscopic parameters, which distinguished falsetto from other qualities.

It is important to note that when interpreting the laryngoscopic parameters, the distance between the vocal folds and the laryngoscope must be taken into consideration. For instance, the opera quality is characterized by a lower larynx position, resulting in the vocal folds being furthest from the laryngoscope and, consequently, the shortest length of vocal folds among all qualities. However, the FVFmid/APlength ratio for opera was found to be the highest among all qualities, indicating that the opera quality was produced with the most significant degree of false vocal fold (FVF) retraction. In contrast, the falsetto quality produced the highest values for parameters such as the length of the membranous part of the vocal folds, maximum amplitude, FVF width, and AP length. Therefore, while opera and falsetto are at opposite ends of the laryngoscopic parameter spectrum, they represent unique and distinctive qualities.

In contrast, the twang quality, identified in the third factor, displayed the lowest FVFmid values and therefore the greatest degree of FVF constriction, placing it at the opposite end of the spectrum from opera in terms of supraglottic constriction. However, the laryngoscopic measurements of the other qualities had significant overlap, making them difficult to distinguish from one another.

4.2. GAT parameters

For the majority of qualities, most GAT parameters, like the laryngeal parameters, showed a dependence on voice pitch. Falsetto produced the highest values for closing quotient (ClQ), amplitude quotient (AmplQ), peak acceleration, amplitude-length ratio, and the lowest values for speed quotient (SQ) and asymmetry quotient (AsymQ) among all

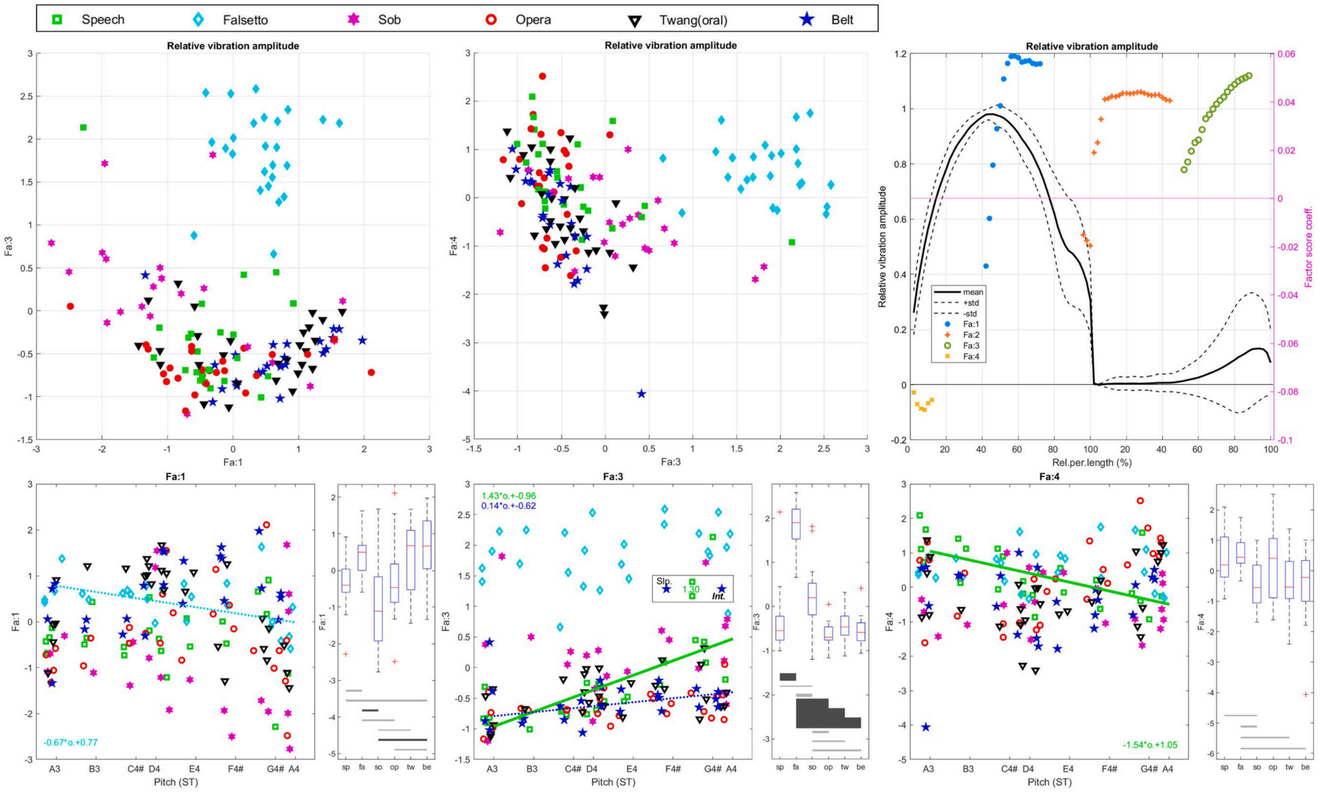

Fig. 9. Results of factor analysis for the relative vibrational amplitude (maximum opening and maximum closing). Upper graphs show the distribution of factor scores and the right graphs show factor score coefficients. Bottom graphs show the relationship of factor scores of each quality with pitch, the tables inside the graphs show comparison of linear trends. The boxplot graphs (bottom right) show mean / median values comparison of factor scores among qualities.

qualities. Speech had the highest values for AsymQ and SQ. Belting was the only quality that systematically decreased open quotient (OQ) with pitch and had the lowest OQ values in the dataset. Belting also had the lowest ClQ and AmplQ values, while exhibiting the highest values for maximum area declination rate (MADR) and the fastest increase in stiffness as a function of pitch.

Sob demonstrated relatively high values of ClQ and AmpQ, albeit lower than falsetto, and low values for stiffness. Moreover, sob was distinctly separated from falsetto by higher values of AsymQ and lower values of peak acceleration and amplitude-length ratio (ALR). Sob also exhibited the lowest MADR value within the dataset. On the other hand, opera and twang did not exhibit extreme values in any parameter, but instead displayed intermediate levels among the analyzed parameters. However, they produced significantly larger ranges of OQ and ClQ values when compared to other qualities.

4.3. *Factor analyses*

Factor analysis of the GAT parameters revealed four main factors that differentiate the different voice qualities. The first factor (OQ + SQ - GAI) divided the qualities into two groups, with speech, falsetto, and sob exhibiting a narrow range of high values, while opera, twang, and belting showed a wider range of lower values.

This factor, which includes OQ and SQ, suggests that the primary difference between qualities may be related to the vibratory mechanism (registers). [59] However, in our study, we were unable to distinguish qualities based on OQ alone, possibly due to unreliable glottal area values resulting from incomplete glottal closure in the posterior region. Nonetheless, OQ and SQ measurements (see Figs. 10 and 11) along the vocal folds used in our study indicated that OQ scores in the 0–90% range of vocal fold length are more effective in discriminating most qualities (excluding twang versus belt). Previous studies have also shown that OQ values derived from the middle part of the vocal folds differ from those obtained from the entire glottal area, and that using OQs from the average value along the vocal fold axis is more appropriate. [53,58].

According to Herbst et al. (2011), [60] the closed quotient is affected by two types of adduction: cartilaginous adduction and membranous medialization. Membranous medialization has a more pronounced effect on the bulging of the middle part of the vocal folds and, thus, on the measured OQ. However, our study found that twang and belt cannot be reliably distinguished based on OQ measurements alone (see Figs. 6 and 10), especially as they exhibit the lowest OQ values. Therefore, it can be assumed that these qualities are produced with the highest degree of membranous medialization.

The difficulty in interpreting OQ is further highlighted by our finding that the first factor, which measured OQ and SQ along the vocal fold axis (i.e., OQ in the range of 10–90% along the axis), was relatively nonspecific as it correlated with a number of other factors in other analyses. Specifically, it correlated with the first GAT factor ($r = 0.69$, $p < 1e\text{-}21$), which includes OQ and ClQ from the total glottal area, as well as the third relative vibration amplitude (RVA) factor ($r = 0.62$, $p < 1e\text{-}16$), which describes cartilaginous part insufficiency. This suggests that OQ is influenced by a number of parameters, making it difficult to interpret on its own.

The ClQ is a parameter from the first factor that is sensitive to the type of phonation when estimated based on glottal flow measurements. Previous studies have shown that the value of ClQ decreases monotonically when phonation changes from breathy to normal to pressed. [55,61] In our study, all qualities except for the speech-opera and twang-belt pairs could be globally distinguished based on ClQ. ClQ decreased in the order of falsetto, sob, speech/opera, and twang/belt. Furthermore, previous studies have shown that ClQ also decreases with increasing intensity. [62–63] In our measurements, the dependence of ClQ and SPL was only moderately strong ($r = -0.43$, $p < 10e\text{-}6$). Only twang and belt could be distinguished based on SPL from the above

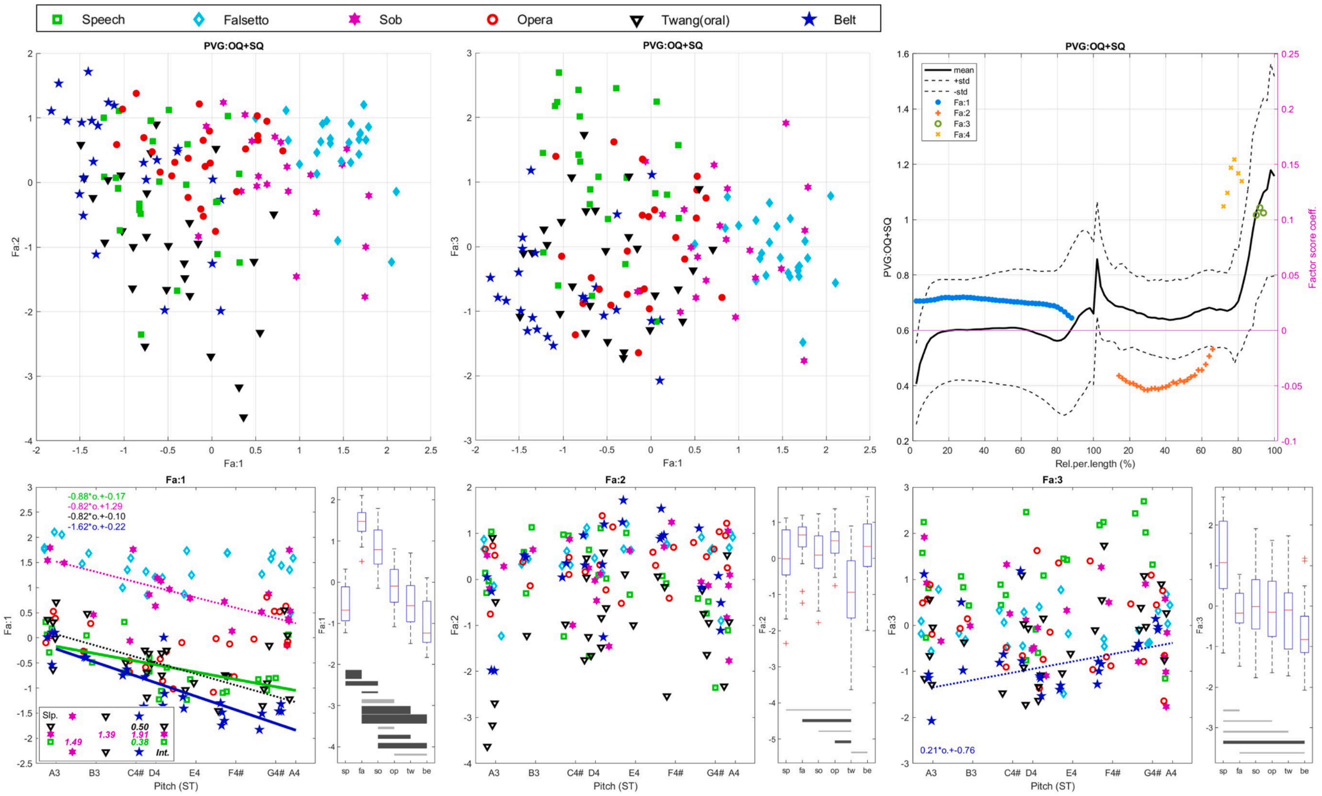

Fig. 10. Results of the factor analysis for open and speed quotients. The left and middle upper graphs show the distribution of factor scores while the right upper graph shows factor score coefficients for the relative length of the vocal folds. The lower graphs show the relationship of factor scores with pitch for each quality. The tables inside the graphs show the comparison of linear trends. The boxplots at the right side of the graphs show mean / median values comparison of factor scores among qualities.

mentioned similar qualities, while speech and opera differed mainly in their pitch-dependent slopes.

The Glottal-Area-Index (GAI), which is the last parameter in the first factor, is derived from OQ and has been shown to be redundant [54]. However, a previous study suggested that an increase in GAI could distinguish between the breathy-to-pressed continuum [64]. In our results, it is not clear whether the first factor of the GAT parameters is more influenced by the type of phonation (cartilaginous adduction) or the type of vocal fold oscillation mechanism (membrane medialization).

Since there is a moderate correlation ($r = 0.55$, $p < 1e\text{-}12$) between the scores of the first factor of the GAT (OQ, ClQ, GAI) parameters and the third factor of the relative amplitude of vocal fold opening vibration minima in the cartilaginous part, it can be assumed that posterior adduction has a dominant influence on the first GAT factor.

The second factor of the GAT parameters (PCV + PAc + MADR) includes peak acceleration, peak closing velocity, and maximum area declination rate (MADR). These parameters have a similar calculation principle and have previously been found to be redundant. Therefore, the use of the amplitude quotient parameter was proposed [54]. However, in our study, the amplitude quotient did not load any factor, and thus, its independence from the aforementioned parameters needs to be considered.

MADR has been reported as a measure of the impact stress loading the vocal folds during collision [65] and allows for indirect insight into the viscoelastic properties of the vocal folds [66]. Furthermore, MADR has been previously shown to successfully differentiate between pressed, flow, and breathy phonation types [57]. MADR depends almost entirely on the ratio of vibrational amplitudes of the lower to upper margins of the vocal fold tissue [65] and is related to vocal intensity. In our study, MADR showed a strong correlation with SPL (0.64, $p < 10e\text{-}6$).

In addition to the phase difference between the upper and lower margins of the vocal folds during oscillations in the modal register, an important factor influencing loudness is the increase in the vocal tract inertia caused by the narrowing of the epilaryngeal tube. This effect is particularly evident in the Estill qualities of twang, opera, and belt, which had the highest SPL values in our study. The narrowed epilaryngeal tube promotes a more constant back pressure in the glottis, causing the MADR to decrease and thus leading to higher vocal economy [67].

However, the MADR results should be interpreted with caution. A recent study by DeJonckere and Lebacq (2020) [68] concluded that MADR was not an adequate measure of impact stress as the glottal closing speed is noticeably reduced just before contact. Therefore, the MADR value may not accurately reflect the actual impact stress during vocal fold collisions.

In our study, the second factor of the GAT parameters was found to best distinguish between falsetto and sob, where the effect of adduction and phonation type (breathy vs. flow) is assumed to be the greatest. Therefore, it is difficult to determine whether the second factor accurately distinguishes between phonation types or is based on membranous medialization of vocal registers. However, the high correlation ($r = 0.7$, $p < 1e\text{-}22$) between the second factor of GAT parameters and the second factor of laryngoscopic parameters (length of membranous portion and anteroposterior length) suggests that this factor is influenced by the activity of the thyroarytenoid (TA) and cricothyroid (CT) muscles. These muscles are highly involved in the determination of the vibratory mechanisms of the vocal folds/registers [69].

Another possible explanation for the dependence of the parameters of the second GAT factor on vocal fold length measurements could be due to the effect of the distance of the glottis from the laryngoscope. The closer the vocal folds are to the laryngoscope, the greater the imaging will be. Therefore, the measurements of any parameters that assess

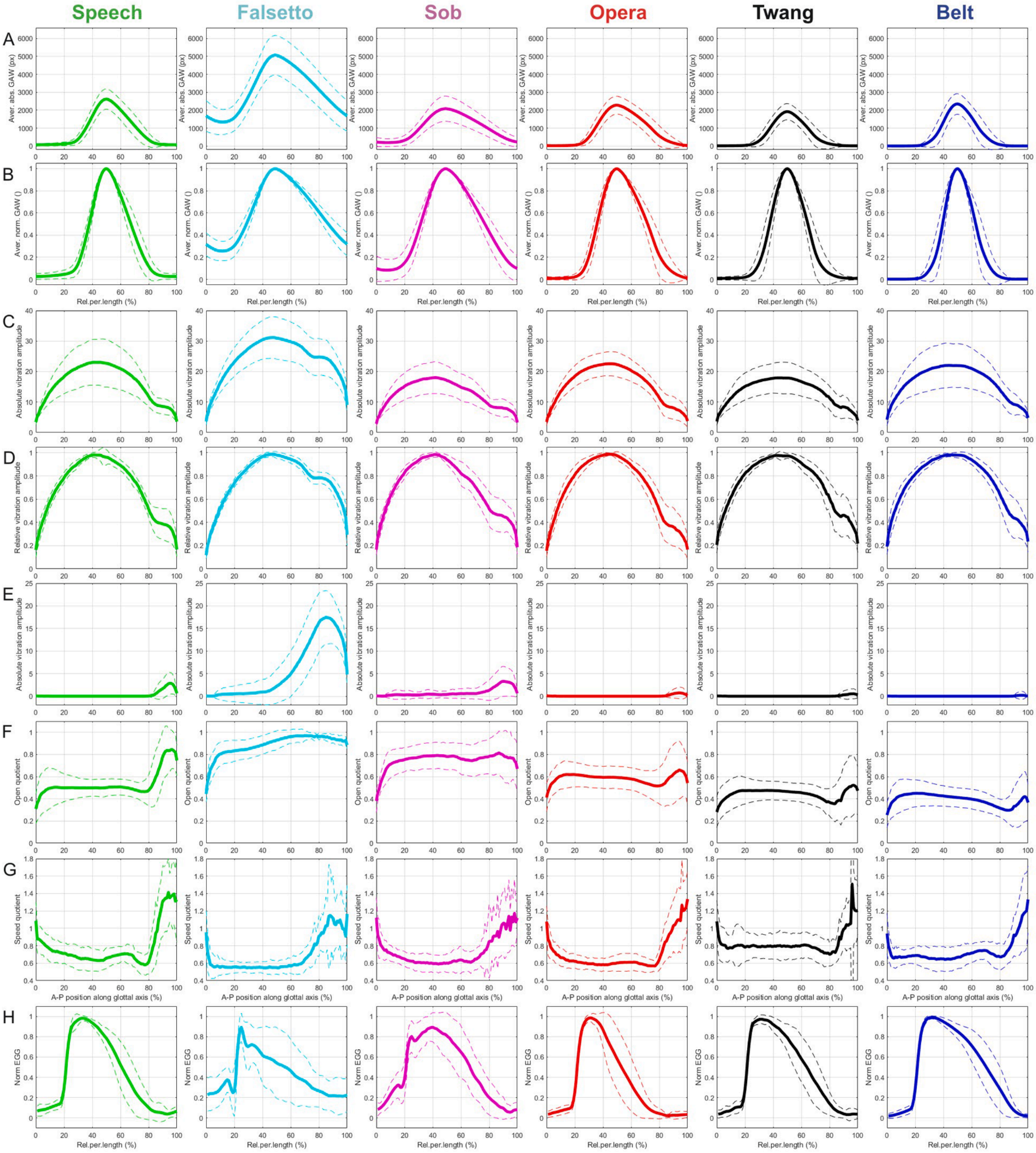

Fig. 11. Averaged values of the waveforms of the measured properties of vocal fold vibration: of absolute (A) and normalized (B) glottal area waveform relative to period length; maximal absolute (C) and normalized (D) vibration amplitude, minimal absolute (E) vibration amplitude, open (F) and speed (G) quotients along glottal length; and normalized EGG wavegrams.

oscillation amplitude or glottal area can be affected, this includes all parameters in the second GAT factor (velocity, acceleration and MADR). A similar issue was previously discussed in a study Patel et al. (2014) [66] that compared MADR between children and adults. The authors recommended the calibrated measurement of the amplitude or the glottal area.

The distance between the laryngoscope and the vocal folds depends mainly on the elevation of the larynx, which is a prescribed fundamental figure among Estill qualities. A low laryngeal position and the greatest distance between the vocal folds and the laryngoscope can be assumed for the opera and sob qualities; a medium laryngeal position is typical for speech and falsetto; and a high position should be expected for the twang and belt qualities. An important part of working with the Estill qualities is the gradual change in laryngeal height with increasing voice pitch. In this study, all measurements of vocal fold length and width showed the largest dimensions for the falsetto quality. This can be explained by Estill's description of falsetto as the only quality in which a stiff body-cover configuration of the vocal folds is used, causing them to be significantly stretched.

According to Estill, the vocal folds are stretched posteriorly creating a glottal chink in the posterior part of the vocal folds [4]. Consequently, this produces breathiness in the voice making the falsetto quality to closely resemble breathy phonation.

From a vocological perspective, it is necessary to discuss whether Estill's falsetto involves the same physiological process as the traditional falsetto/head register, where the vocal folds are assumed to be stretched mainly by the tilting of the thyroid cartilage [70]. While the tilting of the thyroid cartilage is included in the Estill technique, it is not an essential part of falsetto production. Instead, it is a mandatory element for producing qualities such as sob, twang, and opera.

Another Estill figure that may influence the true length of the vocal folds is the thick condition of the body-cover figure. The thick vocal fold condition is required for the speech, belt, and opera qualities, however opera can also be produced using thin folds. When using thick vocal folds, a more significant activation of the TA muscle is necessary. As a result, it is possible to expect a shortening of the vocal folds, as well as increased cartilaginous adduction and membranous medialization. Phonation using thin vocal folds (e.g. sob, twang) should require less TA adduction and activity.

The position of the laryngoscope and vocal folds may have also been influenced by the activation of the aryepiglottic sphincter. A wide opening, as observed during speech, falsetto, and sob, allows for a relatively unobstructed view of the vocal folds from above, facilitating the approach of the laryngoscope to the vocal folds without having to elevate the position of the larynx. During opera, twang, and belt techniques, an epilaryngeal narrow tube is formed, requiring a more posterior and rotated position of the laryngoscope, which is further away from the vocal folds. A study has also demonstrated that different vocal modes, such as neutral, falsetto, curbing, overdrive, and edge, result in different visualizations of the vocal folds, varying between narrow and wide conditions [18].

In falsetto, our measurements of the length of the membranous portion were the longest and most distinct from the measurements obtained in other vocal qualities. The mean values of the other vocal qualities were indistinguishable from each other. However, they were relatively well-differentiated based on the line intercepts as a function of pitch. The measured length of the membranous portion decreased in the following order: belt, speech, sob, twang, and opera, with the smallest length observed in the opera technique. Likewise, the overall vocal fold length had the longest and most distinct values for falsetto. The vocal fold length decreased from speech (with the steepest slope with increasing pitch) followed by sob, belt, twang, and the smallest length was observed for opera.

The longest display of the vocal folds in falsetto may be due to the combination of the wide aryepiglottic tube with the close position of the endoscope, the medial position of the larynx, and the stretching of the vocal folds (using a stiff setting of the body-cover figure). In contrast, the opera technique had the shortest dimensions of the vocal folds due to the low larynx position and unfavorable visualization conditions caused by the narrow aryepiglottic sphincter. Additionally, the vocal folds may have been shortened due to the thick body-cover setting and pronounced activation of the thyroarytenoid muscle.

The third factor of the GAT parameters consists of the speed quotient and asymmetry quotient. These parameters were previously found to be redundant and dependent on ClQ [54]. According to our measurements, they formed a separate factor distinguishing speech, falsetto, and sob from the other qualities.

The SQ parameter calculated from the electroglottographic signal monotonically was previously found to decrease with voice pitch and was able to distinguish legit (i.e., the most comparable CCM style to classical singing) from belt [71]. In our study, it decreased systematically, but only for belt, opera and falsetto. According to our measurements, the belt had higher SQ values only relative to falsetto and sob.

Previous research has suggested that the SQ increases with vocal intensity [72]. However, we could not directly confirm this association in our study, as we did not measure multiple intensity levels for each vocal quality. Nevertheless, our findings support the notion that SQ values are related to voice quality rather than sound pressure level (SPL). Specifically, we observed a consistent increase in SQ values from falsetto, sob, opera to twang/belt, which also corresponded to a similar increase in SPL.

The SQ values along the longitudinal axis of the vocal folds were relatively stable for each quality in the range of 10–80% from the anterior commissure. On average, SQ ranged from 0.5 (sob, falsetto) to 0.95 (twang), which are comparable to SQ values reported for comfortable phonation in both males and females, rather than being specific to females only [53]. As such, it should be noted that the results of this study may not be representative of typical comfortable phonation in female subjects.

The **fourth factor** of the GAT parameters was primarily determined by the Amplitude-Length-Ratio in our study. This finding aligns with previous research indicating that vocal fold length and oscillation amplitude are dependent on voice pitch [73].

If we imagine a three-dimensional representation of the first, second and third GAT factors, we can easily distinguish the 4 qualities located at the vertices of the imaginary tetrahedron.

Belt, which is the only quality with complete closure of the glottis in the posterior part, has the lowest values in the first GAT factor and intermediate values in the second and third factors. This suggests that the first factor is related to cartilaginous adduction of the vocal folds. Opera and twang, which share aryepiglottic narrowing with belt, have intermediate values in the first GAT factor. Yanagisawa et al. (1989) [7] also reported this narrowing in these qualitie. In contrast, speech, sob, and falsetto higher values in the first GAT factor. These qualities do not exhibit aryepiglottic narrowing according to Estill's prescription. Therefore, the first GAT factor can be interpreted as a dimension that reflects the overall effect of cartilaginous adduction, which can be induced by the degree of aryepiglottic narrowing.

The qualities that have high values of the first GAT factor are distinguishable in the first and second GAT factor plane and also in the second and third GAT factor plane.

Falsetto has high values of the second GAT factor and the lowest values of the third, while sob has low values of the second and medium values of the third GAT factor. Speech has medium values in the second GAT factor and high values in the third GAT factor.

The second GAT factor was related to peak vocal fold acceleration and MADR, which are mainly related to membranous medialization, and was related to laryngoscopic length parameters, which indicate the effect of CT and TA muscles, therefore we are inclined to conclude that the second factor was mainly conditioned by vocal register.

The third GAT factor (SQ, AsQ) is related to phonation type and body-cover figure according to Estill. It increases from falsetto/breathy/stiff to sob/flow/thin to speech/neutral/thick.

Although this study provides valuable insights into the possibility of distinguishing six voice qualities from Estill Voice Training, we acknowledge the limitation of using a single subject for the assessment. It is important to note that this study was designed as a pilot investigation, primarily focusing on refining the measurement methodology and analyzing the associated parameters. As such, the findings are preliminary and may not be generalizable to a larger population. To address this limitation and enhance the robustness of our results, future research will involve a larger sample size to ensure greater statistical power and improve the generalizability of the findings.

5. Conclusion

High-speed imaging during singing in 6 Estill qualities allowed the identification of 4 basic factors based on measurement of glottal area waveform parameters. When combined with measurements of vocal fold dimensional parameters, electroglottography, and vocal fold vibration parameters these factors can be used to assess physiological functions of vocal apparatus control.

The first group of parameters (open quotient, closing quotient, and Glottal-Area-Index) was influenced by posterior adduction of the glottis, distinguishing belt quality from others while also suggesting a significant influence of the aryepiglottic sphincter in this factor.

The second factor (peak acceleration, peak closing velocity, and MADR) was the only factor that contained parameters derived from the glottal area amplitude and glottal amplitude with uncalibrated vocal fold length suggesting a relationship with vocal registers and laryngeal height. For a more accurate assessment, future studies should incorporate a calibration method for the image analysis.

The third factor (speed quotient, asymmetry quotient) was best related to body-cover figure and phonation type.

The fourth factor was related to amplitude-length-ratio. This factor had a lesser influence in the classification of the six singing qualities.

The results suggest that Estill voice qualities can be distinguished on the basis of vocal fold oscillation, which reflects the vocal apparatus setup during Estill figures.

CRediT authorship contribution statement

Marek Frič: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Supervision, Project administration. **Alena Dobrovolná:** Conceptualization, Data curation, Validation. **Pedro Amarante Andrade:** Conceptualization, Validation, Investigation, Resources, Data curation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

The purpose of including this appendix is to provide a more detailed comparison of the glottal behavior when measuring Estill qualities and an explanation of the methods utilized in this study.

Fig. 11 not only displays the glottal area waveform (GAW) data, but also presents the electroglottographic (EGG) data. To process the GAW, individual GAW periods from the HSI waveform measurements were resampled to a length of 100 samples and then averaged, with the maximum opening falling within the 50th sample. For normalization, the average GAW period was divided by the maximum value.

To obtain the vibration amplitude maxima and minima of the vocal folds’ opening, as well as the values of CQ and SQ along the anteroposterior axis, phonovibrograms were used. These values were then averaged and calculated in accordance with the methods described in Lohscheller et al. (2013).

The ***absolute GAW*** (row A) exhibit the most significant difference between falsetto and other vocal qualities. Falsetto is mainly characterized by its largest maximum amplitude and the highest degree of glottal insufficiency.

The ***normalized GAW*** (row B) in relation to the maximum opening highlights differences in the shapes of the GAWs. The falsetto quality, with its high values of GA minima, is fundamentally different from the other qualities.

The ***largest absolute vibration amplitude*** (row C) along the glottis is observed in falsetto; it differs from the individual qualities in terms of maximum amplitude, particularly in the posterior part of the glottis.

The ***relative vibration amplitude*** (row D) normalized to maximum amplitude shows differences in glottal width shape. The main difference is located in the posterior part of the glottis in falsetto, where the GW is larger compared to the other qualities.

The ***absolute minimum opening*** (row E) of the glottis differentiated falsetto in particular from other qualities, especially in the posterior part of the glottis, where it reached the largest glottal insufficiency.

The ***open quotient*** (row F) parameter showed the most significant differences between qualities along the glottal axis, with falsetto having the highest values and belt having the lowest. OQ increased in the direction from belt, twang, speech, opera, sob, and falsetto, with some variations in the cartilaginous part of the glottis.

The ***speed quotient*** (row G) revealed considerable discrepancies, the twang achieved the highest values in opposition to falsetto, opera and sob, they reached the lowest values in the middle of the vocal fold’s membranous portion.

With regards to the EGG data, the average EGG pulse shapes were derived from wavegrams, whereby each EGG pulse from the measured high-speed sequence was normalized to values of 0 for the minimum and 1 for the maximum. The normalized pulses were then resampled to 100 samples and synchronized at the maximum of the first derivative of the signal, which was set to 20% of the period length. Afterward, the values of all normalized and interpolated pulses were averaged.

The shape of the ***averaged EGG pulses*** (row H) in falsetto and sob differed significantly from other qualities, according to EGG wavegrams. The shape deformation could have been caused by the inconsistent shape of the EGG pulses in these qualities, with the peak of the first derivative of the EGG signal likely being in an unstable position due to a large insufficiency or lack of vocal fold contact.

The shapes of the resulting average EGG pulses are already common in opera, speech, twang, and belt. Differences in vocal fold contact can be clearly identified, which increase in that order, corresponding to the inverse order based on the open quotient.

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bspc.2023.105366.

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