SPECTRAL ANALYSIS OF VOWELS AND FRICATIVES AT VARIED LEVELS OF DYSARTHRIA SEVERITY FOR AMYOTROPHIC LATERAL SCLEROSIS

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ABSTRACT

Dysarthria due to Amyotrophic Lateral Sclerosis (ALS) affects the acoustic characteristics of different speech sounds. The effects intensify with increasing severity leading to the collapse of the acoustic space of the affected individuals. With an aim to characterize such changes in the acoustic space, this paper studies the variations in band-specific and full-band spectral properties of 4 sustained vowels (/a/, /i/, /o/, /u/) and 3 sustained fricatives (/s/, /sh/, /f/) at different dysarthria severity levels. Effect of dysarthria on spectral features of these phonemes are not well explored. Statistical comparison of these features among different severities for the phonemes considered and among different vowels/fricatives for every severity level using speech data from 119 ALS and 40 healthy subjects indicate the followings. Though all band-specific and full-band features of the three fricatives and most of those features for the four vowels become statistically similar at high severity levels, certain features remain distinguishable. Spectral differences in 0-2 kHz band between /a/ and the other vowels and in the 2-6 kHz band between /a/ and /o/, /u/ persist through all severity levels. Moreover, properties of /f/ remain mostly unchanged with increasing dysarthria severity levels.

***Index Terms*—** Amyotrophic Lateral Sclerosis, dysarthria, severity, vowels, fricatives

1. INTRODUCTION

Dysarthria due to the neuro-degenerative Amyotrophic Lateral Sclerosis (ALS) disease causes progressive disruption in several aspects of speech production including articulation, phonation, respiration, resonance and prosody [1]. Such impairments lead to a range of acoustic abnormalities in different speech sounds, like vowels, fricatives, stop consonants etc. With increasing severity, the nature and degree of the abnormalities change, leading to significant distortion, or even, collapse of the acoustic space of these patients. As a result, intelligibility and naturalness of different speech sounds get severely compromised. In this paper, we aim to analyze the changes in the acoustic space by studying how the frequency band specific spectral properties of different sustained vowels and fricatives change with increasing severity of ALS-induced dysarthria and how those changes affect the discriminability of different vowels and different fricatives. This study can help the clinicians design speech therapies targeted towards improving the phonemes or the spectral characteristics of the phonemes which are more prone to damage at specific dysarthria severity levels. Moreover, the observations can serve as the prior domain knowledge for designing effective speech-based automatic diagnosis methods, dysarthric speech enhancement systems, efficient assistive technologies etc.

Dysarthria due to ALS causes articulatory undershoot during vowel production where the patients fail to achieve the required articulatory configurations for a vowel. Restricted speed and/or range of motion of lips, jaw, tongue and velum, together with their compromised coordination, may lead to these abnormalities [2]. Consequences of these articulatory deficits include centralization of formant frequencies [3], compression of vowel working space [4] and shallower F2 trajectories [5]. Impaired tongue height control often leads to confusion between low and high vowels [6, 7]. The vowel /i/ is reported to undergo the highest decline in intelligibility with increasing dysarthria severity [8]. On the other hand, during the production of fricative sounds, these patients face difficulties in forming constrictions [9, 10]. They are also reported to add unwanted voicing to voiceless fricatives making them sound similar to their voiced counterparts, e.g. /s/ sounds like /z/ [11]. Kumar et al. [12] have attempted to discriminate among /a/, /i/, /o/, /u/ and among /s/, /sh/, /f/ at varied severity levels of ALS-induced dysarthria. They have reported that though the discriminability of both voiced vowels and voiceless fricatives decline with increasing dysarthria severity, vowels are more easily differentiable than fricatives at all severity levels.

A few works have been reported in the literature which perform spectral analyses on vowels and fricatives produced by ALS patients. Tjaden et al. [13] have performed spectral moment analysis on word initial /s/ and /sh/ produced by ALS patients as compared to Healthy Controls (HC). They have observed lower difference between the first moments of /s/ and /sh/ in case of ALS subjects than HCs. However, changes in the frequency specific spectral properties of sustained vowels and fricatives with increasing severity of ALS-induced dysarthria are relatively less explored. To address that aspect, we analyze spectral energy and spectral moments in 8 frequency bands spanning 1 kHz each for 4 sustained vowels - /a/, /i/, /o/, /u/, and 3 sustained fricatives - /s/, /sh/, /f/. We also study the full-band estimates of these features along with the band-specific ones. We perform two types of statistical comparison - (1) among different severity groups for a phoneme, and (2) among different vowels/fricatives for each severity. Speech data from 119 ALS and 40 HC subjects are used. We do not observe any significant spectral difference between the healthy subjects and the ALS patients having no dysarthria in case of any vowels or fricatives except in the 3-5 kHz band of /s/. This is expected as both these groups do not suffer from any speech impairments. Further, we observe that the fricative /f/ does not exhibit significant changes in band-specific spectral properties with increasing severity, whereas properties of /s/ and /sh/ get significantly modified. At the highest severity levels, properties of all 3 fricatives become statistically similar collapsing the fricative space. On the other hands, low frequency (0-2 kHz) characteristics of /a/ remains significantly different from those of the other vowels throughout all severity levels, while the properties of /i/ in the 2-5 kHz band loses its discriminability from other vowels with increase in the dysarthria severity level.

2. DATASET

Sustained utterances of 4 vowels, i.e., /a/, /i/, /o/, /u/, and 3 fricatives, i.e., /s/, /sh/, /f/, were collected from 119 ALS (73M, 46F) and 40 HC (20M, 20F) subjects at the National Institute of Mental Health and Neurosciences, India. The age ranges of ALS and HC are 23 - 81 and 22 - 55 years, respectively. All the subjects were Indian residents having 5 different native languages - Bengali, Hindi, Tamil, Telugu and Kannada. Three speech-language pathologists rated the dysarthria severity of the ALS patients following the 5-point speech component of the ALSFRS-R scale [14] and the mode of the three ratings was taken as the final severity. We categorized 5 dysarthria severities into 3 groups, namely, *severe dysarthric group* (SV) which consists of patients with severity 0 and 1, *mild dysarthric group* (ML) consisting of patients with severity 2 and 3 and *ALS group with no dysarthria* (ND) comprising patients with severity 4. All HC subjects are grouped together as the fourth group (HC) representing *normal speech*. Number of subjects considered for the groups SV, ML, ND and HC are 39, 40, 40 and 40 respectively. Subjects were asked to take a deep breath and prolong a vowel/fricative at comfortable pitch and/or loudness levels. 1 to 3 utterances for each vowel/fricative were collected from a subject depending upon the subject's level of comfort. All speech samples were recorded at 44.1 kHz and then downsampled to 16 kHz. More details about the data collection protocol and the data statistics can be found in [15] and [12].

3. METHOD

We perform band-specific and full-band spectral analysis. The motivation behind taking up the band-specific approach is to check the energy spread across different bands as the severity increases, along with spectral moments, and also within the same severity across different vowels/fricatives. We consider a total of 8 bands, with each band covering a 1 kHz frequency range. For instance, B1 ranges from 0 Hz to 1 kHz, B2 from 1 kHz to 2 kHz, and so on, up to B8, which spans from 7 kHz to 8 kHz. We conduct the analysis using two different types of spectral measures - spectral energy and spectral moments. We consider spectral moments of order 1 to 4, i.e., mean, variance, skewness, and kurtosis, which can serve as the descriptors for central tendency, energy spread, shape, and peakedness, respectively. We calculate all these five different measures separately for each band, for each frame, for every utterance, and then average them across frames. In the case of energy, we normalize the band-wise energies by dividing them by the total energy of the frame before averaging across the frames. Subsequently, we obtain an 8-dimensional vector for each measure for every utterance. We further average these vectors across 1 to 3 repetitions of each vowel/fricatives, resulting in a single 8D vector per vowel/fricative per subject for each of the measures. In addition to the band-specific features, we also calculate full-band moments across all frequencies. We normalize all the waveforms by subtracting the means and dividing by the standard deviation before extracting the features. All the features are computed from the middle $1/3^{rd}$ portion of the utterances only as there might be transient changes in the beginning and end portions. All feature extractions and experiments are carried out using MATLAB R2018b.

We perform the statistical significance tests by following Multiple Comparison test with critical value type being Tukey's Honestly Significant Difference Procedure [16] at 1% significance level. This Multiple Comparison test compares the means of different groups to test the hypothesis that they are all equal. The result tells us which pairs of group means are statistically different. For each severity group, we compare each band-specific and full-band measure across the vowels and the fricatives. Also, for each vowel/fricative, we compare across different severity groups. In this way we analyse both severity wise changes as well as vowel/fricative wise changes within severity.

4. RESULTS AND DISCUSSION

4.1. Analysis of Vowels

Fig. 1 summarizes the statistical comparison results for spectral energy (E), mean (M) and variance (V) of vowels at different frequency bands B1-B8. The left half of the figure shows comparison among different severity groups for each vowel and the right half shows the comparison among different vowels at each severity level. Each cell of a lower triangular matrix in the figure denotes the statistical test outcome for comparison between the pair of feature sets corresponding to the respective row and column. The value 1 (marked in green) represents a significant difference between the competing feature sets, whereas the value 0 (marked in red) represents the absence of any statistically significant difference.

First, let us consider the vowel wise comparisons of different severity groups (left half of Fig. 1). All of spectral energy, mean and variance in the higher B7-B8 bands of /a/ and the lower B2 band of /i/ differ significantly between SV group and others, except only the B8 energy of /a/ between SV and ND. Significant differences w.r.t. spectral mean of /a/ in B1 are also observed between SV and ML/ND groups. Moreover, SV and ML groups differ significantly in the B4 band of /a/ in terms of energy and mean. HC differs significantly from SV in B4 and B7 bands of /i/, while differing from ML in the B4 and B5 bands. For /o/ and /u/, the major severity-wise differences are w.r.t. spectral mean. In B2 and B4 bands of both vowels, SV group differs significantly from others w.r.t. spectral mean. Same is also observed in B6-B8 bands for /o/ and B6 for /u/, except a few cases. SV-ND pair in B6 band and SV-ML pair in B7 band do not have significantly different spectral mean. Differences w.r.t. energy between SV and ND in B1-B2 bands and between SV and HC in B6-B7 bands of /o/ are also observed. The spectral variance at the highest frequency band B8 of /o/ differs significantly between SV and other severity groups, while those of B6-B7 bands differ between SV and HC only. The variances in the B2 band for both /o/ and /u/ are found to be different for SV and ND groups. Lastly, differences between SV and HC are encountered in B3, B4 and B7 bands as well. It is to be noted here that there exists no significant difference between ML-ND and ND-HC pairs in any frequency band of the 4 vowels being considered.

While comparing different vowels at each severity level (right half of Fig. 1), it is observed that, the significant differences of /a/ with the other 3 vowels at B1-B2 bands and with /o/,/u/ at higher bands are mostly preserved at all severity levels. Additionally, for SV, differences between /a/ and /o/, /u/ arise w.r.t. spectral energy in the B3-B6 bands. On the other hand, though /i/ differs significantly from others in B3-B5 bands for HC group, these differences gradually become insignificant with increasing dysarthria severity level.

Vowel wise comparison

Band		/a/			/i/			/o/			/u/		
		SV	ML	ND	SV	ML	ND	SV	ML	ND	SV	ML	ND
		E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V
B1 (0-1 kHz)	ML	0 1 0			0 0 0			0 0 0			0 0 0		
	ND	0 1 0	0 0 0		0 0 0	0 0 0		1 0 0	0 0 0		0 0 0	0 0 0	
	HC	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
B2 (1-2 kHz)	ML	0 0 0			1 1 1			0 1 0			0 1 0		
	ND	0 0 0	0 0 0		1 1 1	0 0 0		1 1 1	0 0 0		0 1 1	0 0 0	
	HC	0 0 0	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0
B3 (2-3 kHz)	ML	0 0 0			0 0 0			0 0 0			0 0 0		
	ND	0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0	
	HC	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0
B4 (3-4 kHz)	ML	1 1 0			0 0 0			0 1 0			0 1 0		
	ND	0 0 0	0 0 0		0 0 0	0 0 0		0 1 0	0 0 0		0 1 0	0 0 0	
	HC	0 0 0	0 0 0	0 0 0	1 1 0	1 1 1	0 0 0	0 1 0	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0
B5 (4-5 kHz)	ML	0 0 0			0 0 0			0 0 0			0 0 0		
	ND	0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0	
	HC	0 0 0	0 0 0	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
B6 (5-6 kHz)	ML	0 0 0			0 0 0			0 1 0			0 1 0		
	ND	0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0		0 1 0	0 0 0	
	HC	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0
B7 (6-7 kHz)	ML	1 1 1			0 0 0			0 0 0			0 0 0		
	ND	1 1 1	0 0 0		0 0 0	0 0 0		0 1 0	0 0 0		0 0 0	0 0 0	
	HC	1 1 1	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0
B8 (7-8 kHz)	ML	1 1 1			0 0 0			0 1 1			0 0 0		
	ND	0 1 1	0 0 0		0 0 0	0 0 0		0 1 1	0 0 0		0 0 0	0 0 0	
	HC	1 1 1	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 1 1	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0

Group wise comparison

Band		SV			ML			ND			HC		
		/a/	/i/	/o/	/a/	/i/	/o/	/a/	/i/	/o/	/a/	/i/	/o/
		E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V	E M V
B1 (0-1 kHz)	/i/	1 0 1			1 1 1			1 1 1			1 1 1		
	/o/	1 0 0	0 0 0		1 0 1	0 1 0		1 0 1	0 1 0		1 0 1	0 1 1	
	/u/	1 0 1	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	1 1 1	0 1 0	0 0 1
B2 (1-2 kHz)	/i/	1 1 1			1 1 1			1 1 1			1 1 1		
	/o/	1 1 0	0 0 0		1 1 1	0 0 0		1 1 1	0 0 0		1 1 1	0 0 0	
	/u/	1 1 1	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0	1 1 1	0 0 0	0 0 0
B3 (2-3 kHz)	/i/	0 0 0			0 0 0			0 0 1			1 1 1		
	/o/	1 1 0	1 1 1		0 1 0	0 1 0		0 0 0	0 1 1		0 1 0	1 1 1	
	/u/	1 1 0	1 1 0	0 0 0	0 1 0	0 1 0	0 0 0	0 0 0	0 1 1	0 0 0	0 1 0	1 1 1	0 0 0
B4 (3-4 kHz)	/i/	0 0 0			0 0 0			0 0 0			1 1 1		
	/o/	1 1 0	0 0 0		0 1 0	0 0 0		0 1 0	1 1 1		0 1 0	1 1 1	
	/u/	1 1 0	0 0 0	0 0 0	0 1 0	0 1 0	0 0 0	0 1 0	1 1 1	0 0 0	0 1 0	1 1 1	0 0 0
B5 (4-5 kHz)	/i/	0 0 0			0 0 0			0 0 0			1 1 1		
	/o/	1 1 0	0 0 0		0 1 0	0 1 0		0 0 0	1 1 0		0 0 0	1 1 1	
	/u/	1 1 0	0 0 0	0 0 0	0 1 0	0 1 0	0 0 0	0 1 0	1 1 1	0 0 0	0 1 0	1 1 1	0 0 0
B6 (5-6 kHz)	/i/	0 0 0			0 0 0			0 0 0			0 0 0		
	/o/	1 1 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0		0 1 0	0 0 0	
	/u/	0 1 0	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0	0 1 0	0 1 0	0 0 0	0 1 0	0 0 0	0 0 0
B7 (6-7 kHz)	/i/	0 0 0			0 0 0			0 0 0			0 0 0		
	/o/	0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0		0 1 0	0 1 0	
	/u/	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 1 0	0 0 0	0 0 0	0 1 0	0 1 0	0 0 0
B8 (7-8 kHz)	/i/	0 0 0			0 0 0			0 0 0			0 0 0		
	/o/	0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 0 0		0 0 0	0 1 0	
	/u/	0 0 0	0 1 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 1 0	0 0 0

Fig. 1. Vowel wise (left half) and group wise (right half) comparisons of band-specific spectral Energy (E), Mean (M) and Variance (V) of vowels; here, value 1 (in green) and value 0 (in red) respectively represent presence and absence of statistically significant difference

Vowel wise comparison

	/a/			/i/			/o/			/u/		
	SV	ML	ND	SV	ML	ND	SV	ML	ND	SV	ML	ND
	S K	S K	S K	S K	S K	S K	S K	S K	S K	S K	S K	S K
ML	0 0			0 0			0 0			0 0		
ND	0 0	0 0		0 0	0 0		0 0	0 0		0 0	0 0	
HC	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0

Group wise comparison

	SV			ML			ND			HC		
	/a/	/i/	/o/	/a/	/i/	/o/	/a/	/i/	/o/	/a/	/i/	/o/
	S K	S K	S K	S K	S K	S K	S K	S K	S K	S K	S K	S K
/i/	1 1			1 1			1 1			1 1		
/o/	0 0	0 0		1 1	1 1		1 1	0 0		1 1	1 1	
/u/	1 1	0 0	0 0	1 1	0 0	0 0	1 1	0 0	0 0	1 1	0 0	1 0

Fig. 2. Vowel wise (left half) and group wise (right half) comparisons of full-band spectral Skewness (S) and Kurtosis (K) of vowels; here, values 0 and 1 represent the same as mentioned in the caption of Fig. 1

Fig. 2 illustrates the statistical test results for full-band skewness (S) and kurtosis (K) measures for vowels. It can be observed that /a/ differs from all of /i/, /o/, /u/ w.r.t. to both skewness and kurtosis for ML, ND and HC groups. In case of SV, difference with /o/ becomes insignificant while the others are maintained. No inter-severity differences of skewness or kurtosis are observed in case of any vowel.

We do not report the full-band mean and variance comparison results and band-specific skewness and kurtosis comparison results, as no significant pattern is observed in those cases.

4.2. Analysis of Fricatives

As illustrated in Fig. 3 (left half), in case of the fricative /s/, SV and ML differs significantly w.r.t. mean in high frequency B6-B8 bands, w.r.t. energy in B7 band and w.r.t. all of energy, mean and variance in the B1 band. Differences between SV and ND exist primarily in all bands except B2-B3, whereas those between SV and HC are prevalent in all bands except B3-B5. Moreover, ML differs from ND primarily in B1 and B5 bands and from HC in B1 and B8 bands. The only difference between ND and HC observed in this paper is in the spectral energy, mean and variance in the B4-B5 bands of the fricative /s/. These two groups are not expected to differ much as both of these do not have any impairments in speech functions. In case of /sh/, SV and other groups differ significantly in terms of spectral mean of all bands except B2-B3 and except the ML vs. SV case in band B6. The spectral energy, differs between SV and ML in B1 and B6 bands, between SV and ND in B1, B4 and B5 bands and between SV and HC in B1 and B4-B6 bands. The spectral variance, on the other side, primarily differs between SV and HC groups in B1, B5 and B6 bands. Most of the frequency specific spectral properties of /f/ remain unchanged with increasing dysarthria severity level except a few. The spectral mean of B1 differs significantly between SV and other severity groups while the spectral energy of that band differs significantly between SV and ND/HC. Also, HC differs from SV in terms of both energy and spectral mean of /f/ in the B8 band.

While analysing the discriminability of the fricatives at different dysarthria severity levels (right half of Fig. 3), we observe that, /f/ differs significantly from /s/ and /sh/ in B1, B2 and B6 bands for HC, ND and ML groups. Also, /f/ shows significant spectral differences with /sh/ in B4-B6 bands and with /s/ in B6-B8 bands for all severities except SV. The differences between /s/ and /sh/ are observed primarily in the cases of HC and ND groups in B3 and higher bands.

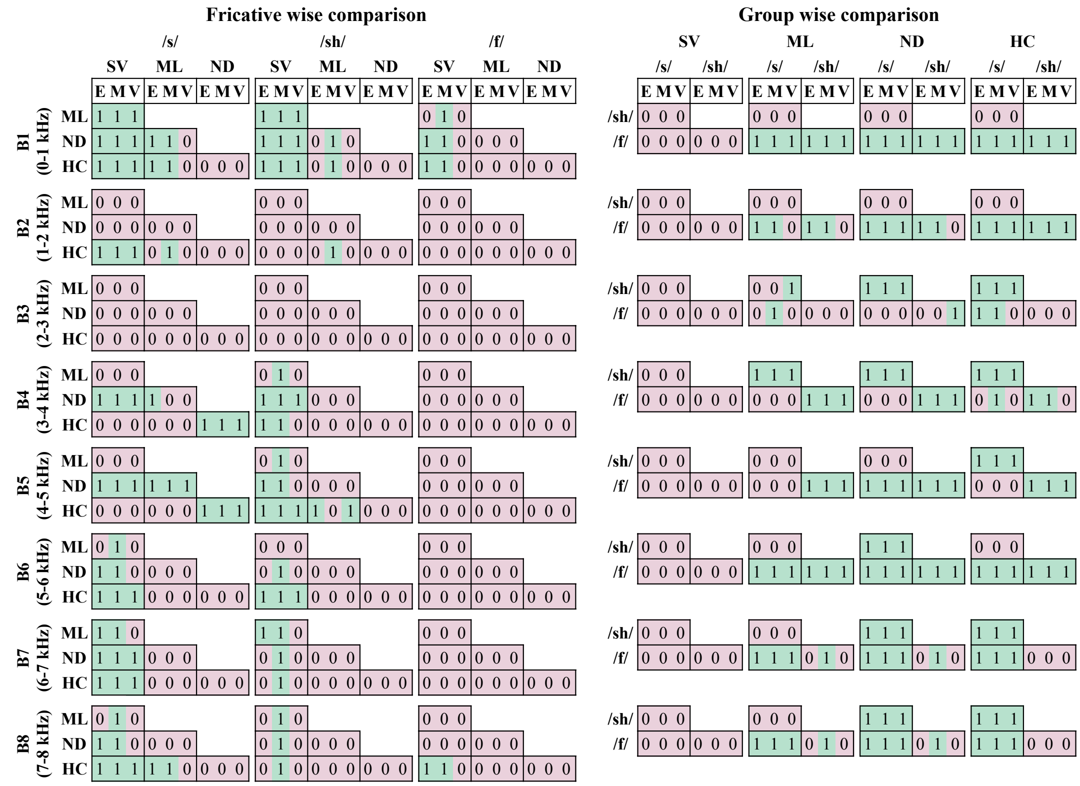

Fig. 3. Fricative wise (left half) and group wise (right half) comparisons of band-specific spectral Energy (E), Mean (M) and Variance (V) of fricatives; here, values 0 and 1 represent the same as mentioned in the caption of Fig. 1

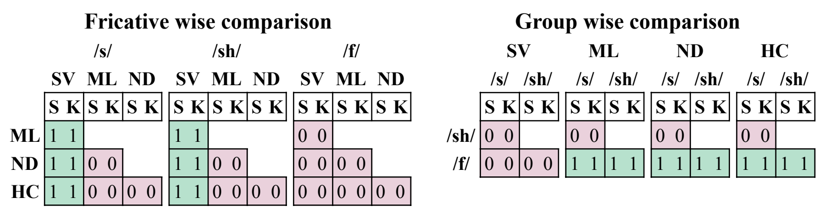

Fig. 4. Fricative wise (left half) and group wise (right half) comparisons of full-band spectral Skewness (S) and Kurtosis (K) of fricatives; here, values 0 and 1 represent the same as mentioned in the caption of Fig. 1

These spectral differences between different fricatives reduce with increasing severity making all three fricatives statistically similar in terms of all of energy, mean and variance features of all bands in the case of the SV group, and thereby, collapsing the fricative space.

Lastly, Fig. 4 illustrates the statistical test results for full-band skewness and kurtosis measures for fricatives. SV differs from the other groups w.r.t. both parameters for /s/ and /sh/. However, /f/ do not show any severity wise changes in these features, which agrees with the behaviour of /f/ in terms of the other spectral properties described before. While comparing among fricatives, we observe that, both skewness and kurtosis of /f/ differ significantly from /s/ and /sh/ in case of all severity groups except SV, in which case the differences become insignificant. Moreover, no difference between /s/ and /sh/ w.r.t. these features is observed at any severity level.

Altogether, these observations on the fricatives might indicate that /f/ is less affected with increase in dysarthria severity, whereas, /s/ and /sh/ undergo significant changes and collapse towards /f/ at the highest severity level. Similar to the vowel case, we do not observe any significant patterns in the full-band mean and variance comparison results and band-specific skewness and kurtosis comparison results for fricatives. Hence, those are not reported.

5. CONCLUSION

In this paper, we analyse band-specific and full-band spectral energy and spectral moments among different dysarthria severity groups for particular vowels and fricatives as well as among different vowels/fricatives for each dysarthria severity group. Fricative /f/ is observed to preserve its spectral properties whereas /s/ and /sh/ significantly change with increase in severity, thereby making the spectral properties of all three fricatives statistically similar at the highest severity level. In the case of vowels, though the differences in several spectral properties collapse with increasing severity, some distinguishable features remain, like, /a/ remains significantly different from the other three vowels /i/, /o/ and /u/ in the 0-2 kHz band at all severity levels. In the future, we would like to explore the spectral properties of stops, diphthongs and syllables with consonant-vowel transitions. We also plan to extend this study to other neurodegenerative diseases, like Parkinson's disease.

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