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Intelligible Transformation Techniques towards Enhancing the Intelligibility of Dysarthric Speech: A Review

S.Arun kumar *, K.Kavitha†, A.Kumaresan‡
Department of Electronics and Communication Engineering, Kumaraguru College of Technology, Coimbatore-641049
Email: *arunkumar.s.ece@kct.ac.in, †kavitha.k.ece@kct.ac.in, ‡kumaresan.a.ece@kct.ac.in,

***Abstract*—Speech is of prime importance to an individual's participation in the society. However various voice disorders, deafness and muteness limits their taking part in the societal activities. Dysarthria is one such voice disorder that affects the articulation of consonants and vowels causing a substantial decrease in the intelligibility and speech quality. This work summarizes on signal processing algorithms and feature level transformations to improve the intelligibility of dysarthric speech in existing literature. The proposed work throws a light on various approaches to improve the intelligibility of dysarthric speech towards developing an assistive communication device or intelligent interpreter, thereby resulting in faster recovery of dysarthric patients.**

***Index Terms*—Dysarthria, speech therapy, feature transformation, speech enhancement, auditory feedback, intelligibility, voice disorder, naturalness, PESQ, speech enhancer.**

I. Introduction

Speech begins with a thought to communicate in the nervous system, activating the muscles required to produce speech sounds. Speech production and perception are important components of an effective communication [1], [2], [3]. A voice disorder [4] limits an individual from communicating by means of speech. Disorders are caused due to neurological problems, brain injury, drug abuse, physical impairments, vocal abuse, but often the cause is unknown. About 7.5 million people in the United States suffer from voice disorders.

Dysarthria is one such speech disorder resulting from impairment of one or more organs used for speech production: respiration, phonation, resonance, articulation and prosody [6]. The severity of the disorder depends on the area of the nervous system affected. Dysarthria is associated with diseases and conditions that are long-term. Some neurological conditions, such as traumatic brain injury, stroke, brain tumour, brain injury leads to non-progressive dysarthria, where as Hunt- ington's disease, Parkinson's disease or amyotrophic lateral sclerosis (ALS), produce a degenerative dysarthria that de- grades speech over time. Speech degradation happens as there is difficulty in moving the muscles that controls speech [15]. Dysarthria may affect the speed, accuracy, timing, strength and range of speech movements. For instance, patients exhibit a slow rate of speech, but particular words or phrases within that speech utterance may be produced at a faster rate. Further, the tongue and lips are rigid, resulting in a reduced range of movement of speech musculature. As a result, there is a substantial decrease in the intelligibility of speech [16]. Intelligibility varies greatly depending on the severity of the disorder. Individuals with Dysarthria, face problems while communicating with others because of reduced intelligibility. This calls for signal processing techniques to enhance the speech intelligibility at the signal level.

The evolving advancements in signal processing algorithms and machine learning techniques and some of the drawbacks in the conventional speech enhancement method motivated to carry out research in the area of disordered speech enhancement. A conventional speech enhancement algorithm attempts to improve the perceptual speech quality (how a speaker conveys an information) rather than intelligibility (information content in the words) using signal processing operations in time and frequency domain [12], [5]. In a Dysarthric speech enhancement system, the input speech is highly distorted and needs to be modified at the phoneme/word/sentence level to improve the intelligibility and naturalness than speech quality. Feature level transformation between normative and dysarthric speech is used for modifying dysarthric speech.

The main aim of this work is to list various feature level transformations to improve the intelligibility of dysarthric speech in the existing literature. This work has gained significance because the intelligibility enhanced speech can be used as an assistive augmentative device or an intelligent interpreter to improve the quality of life dysarthric patients. Enhanced speech given as feedback could be used as a speech therapy tool; thereby improving the voice articulation of dysarthric patients. High quality synthesised speech enhancer coupled with an automatic speech recognizer (ASR) could be used to improve the Quality of service (QOS) in a voice communication setup.

The paper is organized as follows: Section II describes various feature level transformation techniques and signal processing algorithms to enhance the intelligibility of dysarthric speech; Section III presents a comparison of existing studies in literature on dysarthric speech intelligibility enhancement techniques. Section IV concludes the paper and discusses future scope.

II. Feature Space Transformation Techniques To Improve Dysarthric Speech Intelligibility

There have been many studies on intelligibility enhancement of dysarthric speech. Most research has focused on developing assistive devices to help people with communicative disabilities. Most of the techniques in literature use a speech transformation system between normative and dysarthric speech utterances for improving the intelligibility of dysarthric speech. An attempt to improve the speech intelligibility by modifying the features of dysarthric speech directly rather than comparing with its normative counterpart is also carried out in few literature studies. The generic system architecture of a dysarthric speech enhancement system is shown in Figure 1.

Various feature level transformation techniques and signal processing algorithms used in literature to enhance the intelligibility of dysarthric speech are discussed in detail in this section.

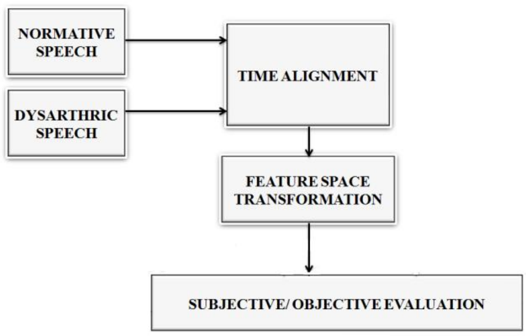

Fig. 1: Generic system architecture of a dysarthric speech enhancement system

F.Rudzicz [4] used acoustic transformations to correct inserted and dropped phoneme errors. Transformation system enhanced the intelligibility of dysarthric speech by performing modifications to the acoustic signal. The transformations were based on retaining the prosodic features and linguistic cues like emotions of dysarthric speech, so as to improve the naturalness of the resynthesised speech. In that study, techniques like tempo morphing and frequency morphing were also used to improve the dysarthric speech intelligibility. The transformation steps used by Rudzicz are outlined in the Figure 2. All these transformations were carried out on TORGO database. The modifications can be performed in a cascade or in a independent manner.

High pass filtering of voiced consonants:
The first modification component involves high pass filtering of voiceless consonants. A tenth order high pass Butterworth filter was used to alter all consonants that are annotated as voiceless.

Correcting mispronunciation errors:
In order to correct the inserted phoneme and dropped phoneme errors, time alignment was performed between the uttered word and the required phoneme to be present in the known

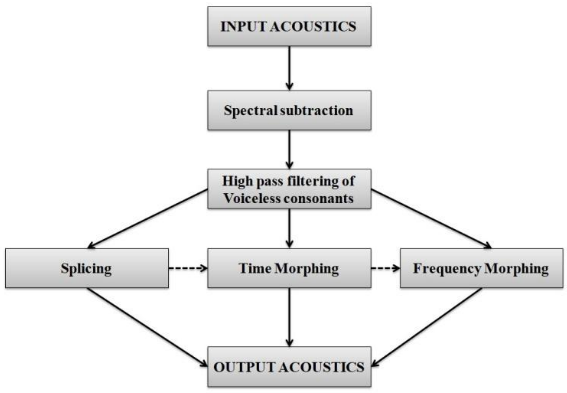

Fig. 2: System architecture to transform dysarthric speech to intelligible speech (Rudzicz)

word. Removal of phoneme insertion and deletion errors was done by adjusting the source speech as per the alignment.

Tempo morphing:
In tempo morphing the modification was performed on time domain. Sonorants in dysarthric speech are quite long and those phonemes are contracted in time. In order to preserve the pitch and frequency characteristics in this transformation, phase vocoder was used.

Frequency morphing:
In frequency morphing, the formant trajectories of the dysarthric speech were replaced with values identified from the known vowel segment. Spectral modification was performed based on the STRAIGHT morphing [7].

The transformed speech was assessed using a set of human listeners who judged the intelligibility and the feasibility of using the modified speech for mediated human to human interaction in the first experiment. In the second experiment, the modified speech was evaluated objectively using an automatic speech recognizer to analyze the possibility of using these transformations in human to computer interaction. The results show that there was a significant improvement in the intelligibility scores in which the phoneme errors are corrected than the formant morphing technique.

Selouni et al. [18] corrected the wrongly uttered phonemes to improve the perceptual evaluation of the speech quality (PESQ) value more than 20%. The transformation system consists of a speech recognizer coupled with a speech synthesis module to aid people with voice disabilities like dysarthria by serving as an assistive device. The proposed speaker dependent hidden markov model (HMM) based automatic speech recognition system improved the intelligibility of dysarthric speech to resemble more natural as compared to their original speech. The flowchart of the proposed system by Selouni et al. is shown in Figure 3.

Automatic Speech Recognition (ASR) was used to identify

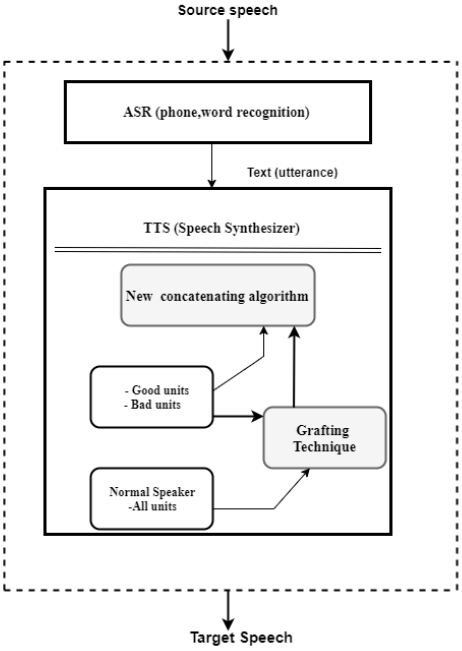

Fig. 3: Assistive system to help dysarthric speaker (Selouni et.al)

the wrongly uttered words to be rectified. Resynthesised speech samples used a new basic unit, a concatenating algorithm and a grafting unit to correct the wrongly uttered phonemes. Concatenating algorithm was used to connect basic words to produce intelligible speech The grafting technique was used to replace the wrongly uttered phonemes in dysarthric speech with a good reference speech. PESQ scores and phoneme recognition accuracy were used to evaluate the intelligibility of the transformed speech.

A.B.Kain et.al [9] claimed that transformation of the vowels of dysarthric speaker to match the vowel space of a normal speaker resulted an intelligibility improvement from 48% to 54%. The transformation system was constructed using analysis, modification and synthesis of features that enhance speech perception. The system architecture for improving the intelligibility of dysarthric speech is illustrated in Figure 4. The transformation consists of finding a trained transformation function that maps features between normative speech data and dysarthric speech data.

Modifications were performed on a frame by frame basis in a pitch synchronous manner to improve the vowel intelligibility. In the modification stage, Formant1 (F1), Formant2 (F2), Formant3 (F3) stable points, energy and vowel duration were used as features for obtaining the transformation function. The set of features used in the transformation function is tabulated in Table I. The optimal feature set was among the 21 feature set estimated by an objective evaluation criteria.

The relationship between the normative speech 'y' and dysarthric speech' x' differs depending on the speaker and not known in advance (apriori). This calls for training a mathematical model between the x and y in order to obtain a transformation function. The transformation function was estimated using a mixture of target data weighted by the posterior probabilities of the Gaussian mixture model. The set that maximizes the maximum posterior probability was considered optimal. A score is defined based on number of times that a correct vowel was identified the right way.

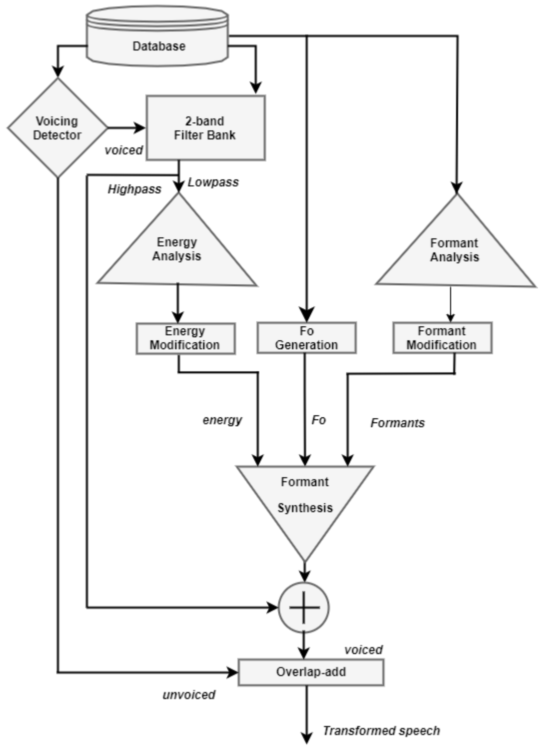

Fig. 4: Dysarthric speech intelligibility improvement system (AB. Kain et.al)

Hesham Tolba et.al [10] achieved a dysarthric speech recognition accuracy improvement from 28% to 71.4% by altering the formant frequencies F1 and F2 to be more identical to expected values. The main idea was to improve the performance of the speech recognizer by using modified dysarthric speech. The dysarthric speech was analyzed to extract formant, energy and fundamental frequency features. For voiced regions, the extracted features were completely changed and fundamental frequency F0 was completely regenerated. The modified features were fed as an input to formant synthesizer. Finally, the original unvoiced regions and the modified voiced regions are assembled to extract the highly intelligible speech output.

Klaat based formant synthesizer was used to synthesize modified speech. The transformed speech was evaluated using perceptual listening test and ASR accuracy.

TABLE I: Feature set used for transformation (A.B. Kain)

Set	Features used
1	F1median+F2median
2	F1stable+F2stable
3	F1median+F2median+duration
4	F1stable+F2stable+duration
5	F1median+F2median+F3median
6	F1stable+F2stable+F3stable
7	F1median+F2median+F3median+duration
8	F1stable+F2stable+F3stable+duration
9	F1stable+F2stable+F3stable+duration+F1slopeleft+F1sloperight
10	F1stable+F2stable+F3stable+duration+F2slopeleft+F2sloperight
11	F1stable+F2stable+F3stable+duration+F1slopeleft+F1sloperight+F2slopeleft+F2sloperight
12	F1stable+F2stable+F3stable+duration+F2sloperight
13	F1stable+F2stable+F2rms
14	F1stable+F2stable+duration+F2rms
15	F1stable+F2stable+F3stable+F2rms
16	F1stable+F2stable+F3stable+duration+F2rms
17	F1stable+F2stable+F2poly
18	F1stable+F2stable+duration+F2poly
19	F1stable+F2stable+F3stable+F2poly
20	F1stable+F2stable+F3stable+duration+F2poly
21	F1stable+F2stable+F3stable+duration+energy

M.Dhanalakshmi et.al [11] used a HMM based speech recognition system along with a speech synthesis module adapted to the voice of the dysarthric speaker to enhance the intelligibility and naturalness of the dysarthric speech. The mispronounced speech uttered by dysarthric person was corrected by the recognition system and the speech was synthesized with a higher degree of intelligibility adapted to the dysarthric speaker's voice. The HMM based speaker adaptive synthesis system is illustrated in Figure 5.

In the training phase, of the speaker adaptive synthesis system 105 dimensional spectral features and 3 dimensional excitation features were used .Context independent 41 monophone models were also trained. Decision tree clustering was used to generate context dependent/pentaphone models.

In the adaptation phase, features like Mel generalized cepstral coefficients and log fundamental frequency were extracted from adaptation data. The models are adapted to the dysarthric speech using Constrained Maximum Likelihood linear Regression (CMLLR) followed by Maximum aposteriori Probability (MAP) adaptation.

In the Synthesis phase a HMM based speaker synthesis system was used .The synthetic speech was generated using mel generalized cepstral coefficients and log fundamental frequency using a Mel Log Spectrum Approximation (MLSA) Filter.

The speech intelligibility and naturalness of the resynthesised speech was evaluated using Degraded Mean Opinion score (DMOS) test. The speaker identity of the transformed speech was evaluated using gaussian mixture model (GMM) based speaker identification system.

ArunKumar et.al [27] proposed a dysarthric speech enhancement system towards developing an effective speech therapy tool using auditory feedback [13]. A feature level transformation was performed between the normative and dysarthric speech to improve the intelligibility. The intelligibility enhanced speech is given as feedback with delay, to a dysarthric patient and if he/she is satisfied with the speech intelligibility this would instill confidence and tempts them to talk more, causing the nerves necessary for speech production

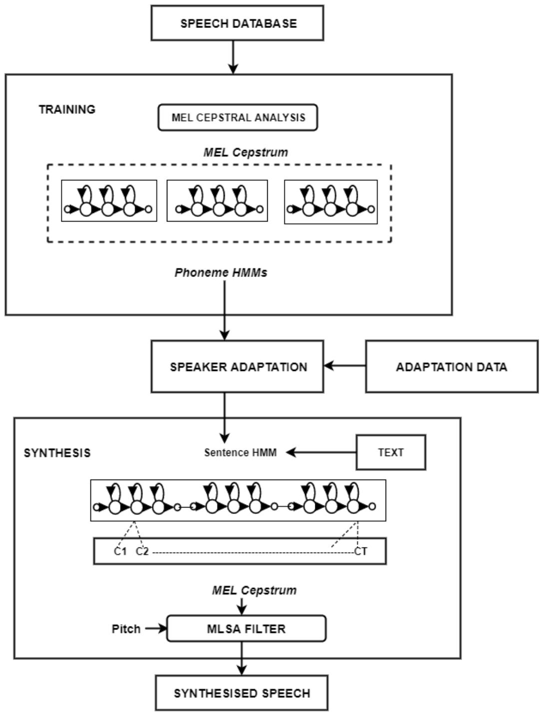

Fig. 5: HMM based adaptive synthesis system (Dhanalakshmi et.al)

to retain its previous form [17]. Thus the proposed system could be used as a therapy tool.

Dynamic time warping [19] was performed between the linear predictive coefficients (LPC) of same utterances of dysarthric speech and normative speech to obtain a feature mapping. The mapped LPC coefficients of normative speech and the LPC residual of dysarthric speech are used to synthesize enhanced dysarthric speech.

Low frequency emphasis was also performed based on applying a warping transformation to LPC analysis filter. The transformation resulted in high intelligibility score and less word error rate.

The quality of the enhanced speech is evaluated used listener based subjective test and PESQ based objective test. The system architecture to improve the dysarthric speech intelligibility is shown in Figure 6.

An assistive communication system was built using a speech recognizer and speech synthesizer to aid dysarthric patients [8]. The proposed system resulted in high intelligibility and recognition rate and was tested in real time on four American speakers with dysarthria and two French speakers with sound substitution disorders. An improvement in correct word recognition accuracy of 60 to 85% and mean opinion score of 4 were obtained in this work.

Kepstrum analysis was used to enhance the quality of the dysarthric speech in cerebral palsy patients. Improvement in

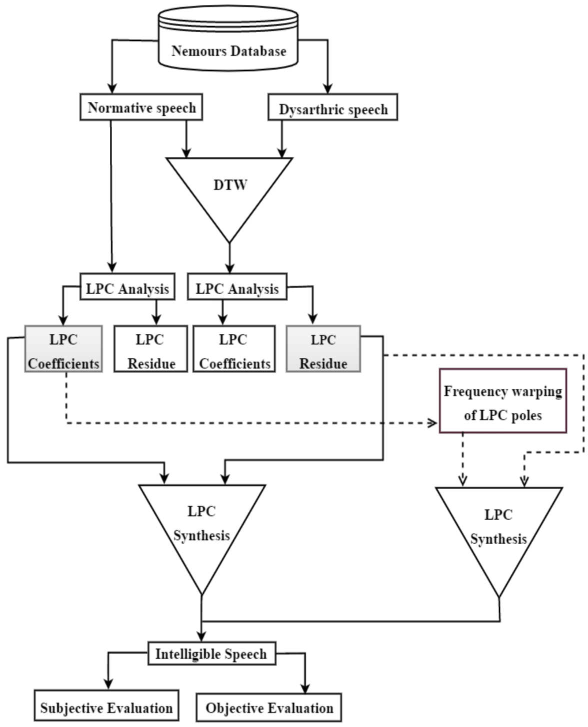

Fig. 6: Dysarthric speech enhancement system (Arunkumar et.al)

the intelligibility of dysarthric speech was achieved using formant shifting and energy modification [20].

A code-book based analysis-synthesis technique was employed in [24] to transform an irregular creaky voice to a regular voice. The linear prediction residuals of irregular speech were replaced by overlap added frames from a code-book, resulting in a regular residual. The efficiency of the proposed transformation technique was assessed using a listening test. The test results show that the roughness of the transformed speech was decreased thereby improving the naturalness of the modified speech.

Divya Das et.al [21] improved the intelligibility by refining the temporal inconsistencies in the dysarthric speech. PESQ-
P.563 and P.862 measures are used to evaluate the objective intelligibility score. A considerable improvement was achieved in the scores.

Saranya et.al [22] used a phoneme replacement technique between dysarthric and normative speech utterances to enhance speech quality. Furthermore, to improve the naturalness in the modified speech energy, formant contour and pitch period were modified similar to normative speech.

Anusha et.al [23] performed manual and automatic modifications based on durational analysis between dysarthric speech and normal speech. In automatic method, dynamic time warping and short term energy were used to modify dysarthric speech utterances. Accuracy improvement of 78.44% and 67.04% was achieved for manual and automatically altered speech using subjective evaluation. A comparative analysis was performed on existing formant re-synthesis system, HMM based text-to-speech system adapted to dysarthric speech and the proposed system based on durational analysis.

A review on acoustic analysis (Time domain analysis, frequency domain analysis, time frequency domain analysis) used in Dysarthric speech was presented in [25]. Various acoustic measures that determine the motor control of speech and voice quality were also discussed in detail. Acoustic-articulatory relationship and articulatory characteristics for dysarthric patients are explained . This work summarizes the impact of modification on various acoustic measures on dysarthric speech intelligibility.

In a automatic speech recognizer, factors like speaker mode, speech mode, speaking style and vocabulary size plays a significant role on recognition accuracy. In Dysarthric speech, speech intelligibility, speech variability and severity of the voice disorder are the factors that exhibit a direct influence over the recognition accuracy of a recognizer ([26].

III. Comparative Study on Techniques to Improve the Intelligibility of Dysarthric Speech

A comparative study on methodology employed on various intelligible transformations and results obtained in significant works, in literature to improve the intelligibility of dysarthric speech is presented in Table II.

IV. Conclusion

In this work, various feature transformation techniques used to enhance the intelligibility of dysarthric speech are explored and discussed. Majority of techniques in literature enhances the quality of the dysarthric speech through modification in the phonemes/vowels, temporal, prosodic and frequency characteristics of speech. There is a significant improvement in intelligibility scores, when more than one transformation is applied on the dysarthric speech. Listener based subjective assessment is performed to determine intelligibility, naturalness and word error rate. PESQ scores, speech recognition accuracy and feature based techniques are the measures used to assess the objective intelligibility score.

From the literature survey it is evident that, a feature space transformation is employed between speech samples of dysarthric and normal population to improve intelligibility. Therefore, a high level feature transformation system would result in increased intelligibility thereby, helping in faster rehabilitation of dysarthric population.

Our future work will focus towards developing algorithms to enhance the intelligibility of dysarthric speech for effective speech therapy and faster recovery of dysarthric patients. Clinically, signal processing algorithms could be used as speech therapy tool or assistive and augmentative communication device to improve the communication capabilities of dysarthric population over the time.

TABLE II: Comparative study on related works to improve the intelligibility of Dysarthric speech

Author	Methodology	Results
Rudzicz	Transformation based on noise reduction, devoicing consonants, tempo morphing and frequency morphing.	Increase in recognition accuracy from 72.7% to 87.9%.
Selouni et al.	The modification is achieved using a concatenating algorithm and a grafting technique to correct wrongly uttered phonemes.	An improvement of PESQ value more than 20% is achieved.
A.B.Kain et al.	Transformation on vowel space and formant frequencies of dysarthric speaker similar to normative speaker.	Improvement in intelligibility score from 48% to 54%.
Hesham tolba et al.	Modification of energy and formant frequency of dysarthric speech identical to normative speech.	Increase in recognition accuracy from 28% to 71.4%.
Dhanalakshmi et al.	HMM based speech recognition system along with a speech synthesis module adapted to the voice of the dysarthric speaker.	Decreased word error rate and increased naturalness by maintaining speaker identity.
Arunkumar et al.	LPC mapping and frequency warping of LPC poles are employed between normative and dysarthric speech samples.	Considerable Improvement in PESQ objective score and DMOS subjective score.
Anusha et al.	Manual and automatic modifications based on durational analysis between dysarthric speech and normal speech.	Improvement in Accuracy of 78.44% and 67.04% was achieved for manual and automatically altered speech using subjective evaluation.
Saranya et al.	Phoneme replacement technique between dysarthric and normative speech utterances.	Improved naturalness and intelligibility in the modified speech.

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Dysarthric speech can be far less intelligible than that of non-dysarthric speakers, causing significant communication difficulties. The goal of our work is to understand the effect that certain modifications have on the intelligibility of dysarthric speech. These modifications are designed to identify aspects of the speech signal or signal processing that may be especially relevant to the effectiveness of a system that transforms dysarthric speech to improve its intelligibility. A result of this study is that dysarthric speech can, in the best case, be modified only at the short-term spectral Behavioral techniques that aim to improve speech intelligibility constitute the bulk of intervention strategies for this population, as the dysarthria does not often respond vigorously to medical interventions. Although several case and group studies generally support the efficacy of behavioral treatment, much work remains to establish a rigorous evidence base.Â In its simplest terms, intelligible speech is that which can be understood by the listener.Â A variety of methods have been developed to reduce the speaking rate of dysarthric patients (for a comprehensive review of these methods see [38]). Eight techniques for quantifying intelligibility of dysarthric speech were compared. Eight dysarthric speakers who represented a wide range of severity were recorded producing single words and sentences. Thirty-two college students performed the following intelligibility quantification tasks: percentage estimates, rating scale estimates, work and sentence transcriptions, word and sentence completions, and word and sentence multiple-choice tasks. Intelligibility scores for transcriptions were compared to estimates and to other objective tasks with the following results: (1) all measurement tech...