Motor equivalence and Speech kinematics in normal and individuals with Dysarthria

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Project Report

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Chapter – I

Introduction

If the acquisition of language can be considered as pinnacle of human cognition, the production of speech may be the paramount characteristic of human physiology. The very simplest act of speech production requires coordinated action among the sub systems of respiration, phonation, resonation and articulation. Further, there exists functional synergy among more than seventy muscles and eight to ten different body parts ranging from the abdominal muscles and the diaphragm to the lips, across all the four sub systems of speech production (Hixon, Mead & Goldman, 1976).

At the articulatory level, the production of speech has been described as a fine motor skill that requires high degree of accuracy and regulated speed (Hirose, 1986).As a highly developed skilled motor behavior, articulation provides a rich environment for observing the functional synergies and coordinative principles that underlie a uniquely human behavior. Even the most subtle act of articulation as in production of a bilabial unvoiced sound /p/, the act of production requires synergies and spatial – temporal coordination between the structures of upper lip (UL), lower lip (LL), the jaw (J). The functional orchestra of these articulators performing in consonance to achieve a particular task sheds light into the tightly knit act of ***articulatory coordination*** that is necessary to achieve the simplest act of speech production.

Articulatory coordination can be defined as a neural control strategy which is superimposed over several potentially independent speech gestures to assure their complementary contribution to the achievement of common 'vocal tract goals' (Hughes & Abbs, 1976). The knowledge of mechanism underlying articulatory coordination is basic to our understanding of speech production, as it describes the involvement of each of the articulator and its abnormalities that contribute towards the disruption of normal speech production. One set of hypotheses concerning the nature of articulatory coordination has been identified with the "***principle of motor equivalence***". Motor equivalence can be defined as the capacity of a motor system to achieve the same end-product with considerable variation in the individual components that contribute to that output. Motor equivalence phenomena are interesting in speech production research because they are an efficient way of addressing fundamental issues: the nature of speech goals and the inter – articulator coordination underlying speech variability.

Motor equivalence is of great interest in the field of speech language pathology because it represents the behavior in which the nervous system controls the multiple degrees of movement freedom (Bernstein, 1967). It is generally accepted that the nervous system employs simplifying strategies to reduce the potentially independent variables (motor units, muscles, joints) in most motor behaviors to a controllable number. Rather than considering each articulator as independently controlled patterns it has been suggested that speech articulators are functionally constrained. That is, rather than explicitly controlling the timing of the different neuromuscular elements involved in the production of a particular sound, the nervous system controls the coordinative requirements of all the active effecters as a unit (Gracco, 1990, 1994).

The normal coordinated act of speech production can be disrupted in several ways one of the possible means it by the damage sustained to the neuromuscular system regulating speech. The common most disruption in normal speech as a result of damage to central nervous system (CNS) is dysarthria. It has been defined as a speech disorder resulting from damage to neural mechanism that regulates speech movements (Netsell, 1986). Changes in articulatory movements associated with dysarthria lead to aberrant speech acoustics and a perceptually recognizable disorder. Most of what we know about the nature of articulatory impairment indysarthria comes from a number of perceptual and acoustic studies (Chen & Stevens, 2001; Kent, Netsell, & Abbs, 1979; Tjaden & Turner, 1997; Weismer, Jeng, Laures, Kent, & Kent, 2001; Weismer, Laures, Jeng, Kent, & Kent, 2000; Weismer, Martin, Kent, & Kent, 1992). Without fine oral and laryngeal control for speech, deviant patterns such as slurred consonants and vowels, hypernasality and excessive or monotonic intonation are produced (Darley, Aronson, & Brown, 1975). Acoustic features of dysarthria include prolongation of speech sounds, vowel/consonant imprecision, slowed consonant–vowel transitions and reduced vowel space (Chen & Stevens, 2001; Kent, Netsell, & Abbs, 1979; Tjaden & Turner, 1997; Weismer, Jeng, Laures, Kent, & Kent, 2001).

Need for the study

Researchers in the field of speech language pathology have used several methodologies to study the existence of motor equivalence strategies in speech production. The earliest methods used were 1) Limiting the degrees of freedom by introducing perturbations (Gay, Lindblom & Lubker, 1981), 2) Changing the physiology of speech production structures by introducing artificial dentures (Jones & Munhall, 2003), artificial palates (McFarland et al., 2004), 3) Altering the feedback information during speech production (Kelso, Tuller & Harris 1983; Ito & Ostry, 2010). These methodologies have been studied extensively and there exists a lack of consensual agreement among the research community towards the outcomes of these studies. The recent approach towards understanding motor equivalence strategies has shifted from perturbation experiments to studying the disordered speech production.

Review of existing literature reveals a dearth of studies that have attempted to investigate the existence of motor equivalence in individuals with disordered speech. Dysarthria, being a disorder of speech and resulting from damage to the neuromuscular substrates responsible for normal speech production, provides a unique opportunity to investigate the existence of motor equivalence in speech. The extensive profiling of articulatory abnormalities associated with dysarthria, summarized in the earlier sections; reflect windows of opportunities to look into the nature and organization of disordered speech production. By considering and carefully analyzing the coordination among the articulators in individuals with dysarthria, one can and possibly, look into the existence and implications of motor equivalence.

There exists a fewer number of studies that have attempted to look into articulatory coordination in individuals with dysarthria (Bartle, Goozée, Scott, Murdoch, &Kuruvilla, 2006; Ackermann, Gräber, Hertrich, & Daum, 1999; Kent et al., 1979; Tjaden, 2003). These studies provide evidence of existence of dyscoordination but do not make any advances to comment or investigate the existence of motor equivalence. Further, these studies consider single articulator movements occurring in simplified phonetic material. These methodological drawbacks hinder the studies from looking into the composite result of multiple articulatory movements and cannot confirm with certainty whether and how neurological diseases affect the individual or collective movements of articulators such as the jaw, tongue, and lips.

The existing literature cited in the earlier paragraphs has considered paradigms such as acoustics or perceptual measures to comment of the nature of articulatory coordination in individuals with dysarthria. One of the physiological paradigms used to study articulatory dynamics is ***kinematic analysis***, which has received less attention with respect to the question of inter – articulatory coordination and motor dynamics in individuals with dysarthria. Kinematic analysis being a dynamic tool provides innumerable opportunities to investigate multiple articulatory movements and also to look into the coordination between various articulators.

Smith, Goffman, Zelaznik, Ying and McGillem, (1995) suggested that Spatio temporal index (STI) is the widely used derived measures in kinematics to study and describe patterning and stability of motor system. The STI is defined as the sum of standard deviations of kinematic waveforms from multiple repetitions of an utterance, which are time and amplitude normalized (Smith et al., 1995). Hence these measures are highly suitable to study the articulatory dynamics of individuals with dysarthria.

Green, Moore, Higashikawa and Steeve (2000) introduced two new analysis techniques called the ‘spatial coupling’ and ‘temporal coupling’ to study the coordination between the articulators. They used Peak coefficients (negative or positive) and their associated lags were derived from the cross - correlationfunctions computed between the treated displacement traces of all possible articulatory pairs. This method of analysis provides a window to estimate the degree of temporal and spatial coupling during the act of inter - articulator coordination. Within the existing review of literature, there are no studies that attempt to look into the inter articulatory coordination in individuals with dysarthria using a kinematic paradigm using these measures.

Considering the grey areas of unanswered research, the present study is an initial attempt in these directions. In a nutshell, we postulate that inferences pertaining to the existence of possible motor equivalence strategies can be made by studying kinematic traces of articulatory coordination between various articulators of individuals with dysarthria and normal individuals. These motor equivalence strategies in individuals with dysarthia would indicate the existence of plasticity, which could serve as the basis for motor rehabilitation when the peripheral motor system is damaged and certain body parts take over for others. Hence the present study is taken to investigate motor equivalence strategies in individuals with dysarthria during the act of inter articulatory coordination as measured on spatial and temporal coupling, with the following aims and objectives.

Aim of the study

The present study aimed to compare STI, spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501

Objectives of the study

1. To analyze and compare movement stability and variability of articulatory dynamics in terms of STI for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501.
2. Further, to investigate inter articulatory coordination as measured on spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501.

Chapter – II

Review of literature

Motor equivalence can be roughly defined as the capacity of a motor system to achieve the same motor task differently. This adaptive capability of the motor system that functions depending on external constraints is called the “plasticity” of the motor system. The plasticity of the motor system allows the Central Nervous System (CNS) to complete the intended motor task appropriately, while taking the constraints into consideration. These constraints can occur in form of the search for efficiency, as demonstrated while lifting an object using our legs rather than using our back, or the need for the parallel execution of other motor tasks, such as speaking and simultaneously writing. Plasticity forms the basis for motor rehabilitation when the peripheral motor system is damaged and certain body part has to compensate by taking over the function of an impaired system.

Speech being a motor act, demonstrates events where the phenomenon of motor equivalence is exhibited. The classic example of motor equivalence in speech is the ability to communicate efficiently when the free movement of jaws is disrupted by a pencil held between the upper and lower teeth. This serves as a disruption to normal way of speaking by restricting the normal movement of jaws. Even though the normal jaw movements are restricted the speakers can change their motor strategies in such a way the listeners are able to perceive what’s being said. These motor strategies employed to compensate for the normal movement of jaws are the strategies of motor equivalence and has been clearly documented in a number of experimental studies.

For example, Hughes and Abbs (1976) conducted experiments on repetitive productions of vowels /æ, i,/ during Consonant-Vowel syllables contexts to study inter - articulatory variability in native speakers of American English. The results of their study revealed that the same distance between the lower lip (LL) and upper lip (UL), different individual positions of the LL, UL and Jaw were reached. The authors conclude with the remark that motor strategy during the production of test stimuli was to keep the labial distance constant. To achieve this, variations in the position of one of these articulators were counterbalanced by coordinated variations of the two other articulators, in order to keep the distance between the lips at a constant value. This is a motor equivalence strategy, one that uses the property where various inter-articulatory configurations can lead to the same inter - labial distance.

Similarly, Maeda (1990) reported the variability of the jaw and the tongue dorsum positions during the production of /i/ and /a/ in varying phonetic contexts among the native speakers of French. The results of the study demonstrated that jaw height and tongue dorsum front-back position cooperated to ensure the achievement of the required vocal tract shape for the production of each target vowel. The authors propose that the ‘vocal tract shape’ to be the motor goal. The common observation across production of both vowels was that insufficiency in the jaw height was maintained by counterbalancing of a more anterior positioning of the tongue, and inversely a high jaw position was associated with a more posterior tongue positioning for the production. For vowel /i/, when jaw position was lowered, the more anterior positioning was associated with an elevation of the tongue with respect to the movement of jaw. The authors opine that this occurred presumably in order to keep the constriction small and anterior enough. For production of vowel /a/, when jaw was lower, the more anterior tongue positioning was demonstrated in order to prevent the reduction of the constriction area in the pharynx.

Methods to study motor equivalence in speech production

Methodologically, motor equivalence in speech has often been investigated through experimental studies. Sometimes these experimental studies have been associated with modeling work, and experimental data have been compared to the results of simulations. The basic idea underlying the design of experimental studies is to generate variability in the realization of the same goal. The following are the experimental methodologies used across literature to study the phenomenon of motor equivalence.

The majority of experimental studies of motor equivalence for speech production, have used perturbation paradigm. The basic notion underlying these paradigms are to bring about significant changes to the normal conditions of production in which a particular motor task is realized. These induced changes disturb the way in which motor strategies are used to fulfill the respective motor task under normal conditions. In the absence of motor equivalence, perturbations would definitely prevent the subjects from fulfilling the motor task. When the motor equivalence strategies exist for a given task, perturbations act as an effective way to study the link between co - ordinated articulatory structures. Further, perturbations allow investigations into degrees of freedom for a given task and how the CNS is interacting with the external constraints to preserve the fulfilment of the intended motor goal. Perturbation studies differ with respect to the level they apply to. The following are the ways of studying motor equivalence in speech production:

1. Perturbations that limit the degrees of freedom of the motor system

Perturbations that limit the degrees of freedom during production task restrict the use of one or more degrees of freedom in achieving the task. These perturbations can be delivered in the following two forms1) ***static occurrences***: where the perturbation is kept constant for the duration of the motor task, and 2) ***varied across of occurrence***, as in perturbations that are applied at a certain time - intervals for a certain brief duration. By looking at the way the CNS uses the remaining unrestricted degrees of freedom to achieve the intended motor task, it is possible to gather interesting information about degrees of freedom. In general, information about the nature of the goal that is conserved in spite of these introduced perturbation, and about the process underlying the development of motor equivalent strategies in the restricted space of the remaining degrees of freedom.

The plethora of existing phonetic studies on different languages has demonstrated that the jaw position can vary during vowel production. This consistent striking observation, together with the fact that speaking is possible with an object held between the teeth, has led to the conclusion that jaw opening is a degree of freedom that can be altered during vowel production. The earliest studies on motor equivalence of speech were applied to the jaw and restricting its degrees of movement. One of the most popular static perturbations of jaw opening has been the introduction of a bite-block (Lindblom, Lubker & Gay, 1981).

Bite-blocks are small rigid acrylic blocks, which range a few millimeters in depth and width. These are held between the lower and upper teeth of the subject to introduce the perturbations. These induced perturbations restrict the jaw to stay at a constant position during the production of speech. Depending on the height of the block, the jaw is fixed either at a high position or at a low position (bite block height=20-25mm).

Another method of introducing perturbation to the jaw involve application of resistive loading to the articulatory structures during the closing movement of a bilabial stop (Folkins &Abbs, 1975; Kelso et al., 1984). The resistive loading to the articulator structure prevents the jaw continuing its upward movement toward the position usually reached under normal conditions in the bilabial stop. However, as long as the resistive loading is not too strong, this induced perturbation does not prevent the fulfillment of the labial closure that is necessary for the production of bilabial stops. Since the labial closure is the result of the combined influences of the Jaw, the UL and the LL positions, the reduced amplitude of the jaw can be compensated for by increase in the amplitude of the movements of the LL and UL.

The models of speech production that takes acoustics into consideration such as the Acoustic theory of speech production (Fant, 1960) have shown that the position and size of the constriction within the vocal tract, and the shape of the lips (spread or rounded) are the two main factors that influence the spectral characteristics (the formants) that are relevant for the perception of vowels. These models have also shown that for the vowels /u/ and /i:/, two different constriction patterns are possible in the vocal tract. A constriction in the palato-velar region is possible in association with a small lip area, or a constriction in the velo-pharyngeal region can be used in combination with a larger lip area. For these vowels, lip opening is one of the degrees of freedom.

Perturbation of the lip opening has been manipulated by Savariaux et al. (1995). The perturbation consists of using a 25mm-diameter tube to prevent the achievement of the small lip required for rounded lips. Based on the acoustic theory of speech production, it is theoretically possible to produce a vowel in the presence of this perturbation by constricting the velo-pharyngeal region of the vocal tract.

2. Perturbations that change the physical conditions of speech production.

A second kind of perturbation deals with the modification of the physical conditions of speech production. The underlying notion of these paradigms is quite different from the earlier ones. It does not involve restricting the degrees of freedom in the speech production system, rather deals with changing the way the articulators interact with the vocal tract boundaries or of changing the dynamical components such as forces applied to the articulators. Under these perturbed conditions, the CNS is introduced with the usual motor control strategies that do not produce the expected effects, either in the articulatory or in the acoustic domain. The ultimate goal of the task, is the production of a phoneme or of a short sequence of phonemes which does not change, but a new strategy would be formed to reach this goal. In that sense it is a motor equivalence problem. Existing motor equivalence strategies for normal production of speech may not be used to the same extent. The CNS has to explore newer paths for motor equivalence and to come up with new motor control strategies in order to reach the same goals as under normal conditions. The purpose of this kind of perturbation experiments is to observe how the CNS explores motor plasticity in the domains of articulatory and acoustics to preserve the achievement of speech goals. These studies provide information on the nature of the goal, the plasticity of the motor system, and on the way new strategies can be developed.

A first example for this type of perturbation is to modify the morphology of the vocal tract. When the morphology of the vocal tract changes, articulatory movements do not shape vocal tract cavities in the same way as under normal conditions. Consequently, the relationship between articulatory movements and acoustics also changes. Perturbations of the vocal tract morphology are classically introduced with artificial palates of different thicknesses (McFarland et al., 1996) or different shapes or with a dental prosthesis in which the upper incisors are longer than under normal conditions (Jones & Munhall, 2003). These perturbations are static. Unexpected and time variable perturbations have also been provided using an inflatable artificial palate (Honda et al., 2002).A more complex perturbation to the speech production apparatus consists of applying a time varying force field to the jaw. The intensity of the force field varies in time as a function of the velocity of the jaw movement: the faster the movement, the stronger the force field. No force is applied both at the beginning and at the end of the movement, since the velocity is zero at these positions. Rather, the force field modifies the mechanical conditions for the displacement between these two extreme positions (Tremblay et al, 2003).

3. Perturbations that change feedback information.

The third kind of perturbation does not affect the speech production system itself. It modifies the way the Central Nervous System can assess whether motor goals are reached by altering oro-sensory (tactile and/or somato-sensory) or auditory feedback. Motor equivalence strategies with altered feedback are different from strategies that are used under normal conditions, since the entire production-perception system is taken into account, and goals are defined in sensory rather than in physical terms. Altered feedback perturbation provides information on the motor control processes underlying the use of motor equivalence strategies, on the role of feedback in the selection of motor equivalence strategies, and on the nature of the speech production goals in the sensory domain.

Altered oro-sensory feedback is frequently produced by applying an anesthetic that reduces the amplitude of oro-sensory feedback, though anesthesia has the drawback of effects that are hard to control in their extent. Anesthesia has been applied to the temporo-mandibular joint, which provides information on jaw position (Kelso, Tuller & Harris, 1983), and to the oral mucosa, which provides tactile feedback information (Kelso, Tuller and Harris, 1983). Recently, Ito and Ostry (2010) perturbed the kinesthetic information provided by the cutaneous receptors in the skin of the face. These receptors provide information on the stretching of the skin, which is influenced by the positioning of the jaw and by the spreading or protrusion of the lips in natural speech. Perturbing this feedback information modifies the perception of the positions of these speech articulators.

A common perturbation consists of restricting the availability of auditory information by presenting very loud white noise (classically 80 to 90 dB) to the subjects via headphones (Kelso & Tuller, 1983; Brunner et al. 2011). This perturbation should be used with caution since it is known to induce significant changes in speech articulation, according to the well-known “Lombard effect” (Summers et al, 1988). Another perturbation, more complex to implement, is altering the spectral characteristics of the speech signal. This perturbation can affect the formant values of vowels in whispered speech (Houde & Jordan, 1998) or in normal speech (Purcell &Munhall, 2006a), the spectral Center of Gravity (COG) of fricatives (Shiller et al., 2009), or the fundamental frequency (Jones & Munhall, 2003). In all these experiments, natural auditory feedback due to acoustic wave propagation in the air and to bone conduction of acoustic vibrations has to be masked. This is why the perturbed auditory feedback is presented to the subjects via headphones and at a relatively high acoustic level (again 80 to 90 dB).

Inter – articulatory coordination in individuals with dysarthria

Ackermann, Hertrich and Scharf (1995), in their study in German put forth that there exists a linear relationship between peak velocity and amplitude. They further suggest that the ratio of maximum displacement to velocity provides a measure of mass normalized stiffness of the assumed spring functions underlying articulatory performance. According to the authors, stiffness represents an important parameter of skilled speech motor processes. They opine that by studying the neurogenic speech motor disorders can reveal insights into the modification of stiffness brought about by the central nervous system with changes in velocity and displacement. To test this hypothesis, the authors used kinematic paradigm to investigate the cerebellar influence on articulatory performance. The objectives of their study were to look into the following 1) the labial gestures of cerebellar patients as well as normal controls in terms of linear trend between peak velocity and peak amplitude 2) the relationship between kinematic slopes of cerebellar dysarthrics and normal controls 3) the discrepancies between slopes of normal controls and dysarthrics for opening and closing gestures.

With respect to the hypothesis and the objectives of the study, the authors measured the excursion of the lower lips during production of sentence utterances by means of a photoelectric movement analyzing system in four dysarthric subjects with atrophy restricted to the cerebellum. Kinematic parameters (amplitude, peak velocity, duration) were computed for the opening and successive closing gesture of the sequences /pap/ and /pa:p/, respectively, embedded into a carrier phrase each. Eight different target words of the type "gepVpe" (V= /a, a:, i,i:,y, y:, u,u:/) printed in bold large letters on a card each were visually presented in quasi-randomized order. Subjects were asked to produce the shown target word embedded into the carrier phrase "lIchhabegelesen" ("I have read"). The study considered the two utterances "lIchhabegepapegelesen" and "Ich habegepappegelesen" for kinematic analysis of lip movements. These two sentences differed in the durational category of the vowel /a/ of the target word ("gepape" = /gepa:pe/, "gepappe" = /gepape/). The remaining 6 test sentences were included for the sake of another study. Eight repetitions of each were recorded. These two test sentences were considered in order to control for vowel length. Since short and long vowels represent distinct phonemes in German, they might differ in the kinematic properties of the underlying articulatory gestures.

The results of the study revealed prolongation of various segments both during syllable repetitions and sentence utterances in cerebellar subjects. Accordingly, the participants of the study showed an increased duration for both phonologically long and short vowels. Short targets were relatively more lengthened than their long cognates. The study thus corroborates the observation of an over proportionate prolongation of short vocalic segments as reported in the literature. A linear increase of maximum velocity with amplitude seems to be a basic organizational principle of arm as well as orofacial and laryngeal movements. The present investigation revealed a similar relationship in lower lip excursions during sentence utterances produced by individuals with cerebellar dysfunction. However, the cerebellar group showed a decreased slope of the computed regression lines for both opening and closing gestures. Thus, the patients performed excursions of given amplitude with reduced peak velocity in comparison to the normal speakers.

Bartle, Gooze, Scott, Murdoch and Kuruvilla (2006) investigated the tongue jaw coordination in individuals with dysarthria following TBI using EMMA assessment. The authors hypothesized that the spatial and the temporal aspects of coordination would be affected in individuals with dysarthria following TBI. For the purpose, the authors considered 9 participants with dysarthria following TBI and 9 neuro – typical individuals, who served as controls for the present study. Both the group of participants underwent a perceptual speech assessment and a physiological instrumental assessment using EMMA.

Participants were required to read ‘The Grandfather Passage’, from which a speech sample was obtained and tape recorded using a SONY Portable Minidisk Recorder MZ-R700. Each participant’s speech sample was later analysed independently by two speech-language pathologists who were unrelated to the study. Participants were instructed to speak at a comfortable speaking rate and volume. The articulatory features, intelligibility and rate sections of the perceptual rating scale, described by FitzGerald et al (1987) were used to analyse each participant's speech. For the articulatory features section (precision of consonants; length of phonemes; precision of vowels) and the intelligibility (overall intelligibility) section, an equal-appearing interval scale of 1–4 was used to mark the severity of disturbances; 1 indicating normal production and 4 indicating severe disturbances. For the rate section (general rate), a scale of 1–7 was used, where 4 indicated normal rate, 1–3 indicated a slow speech rate and 5–7 indicated a fast speech rate. After analysing each participant's speech, two speech-language pathologists were required to diagnose the severity of each participant's dysarthria. Discrepancies between ratings and diagnoses were discussed among the two speech-language pathologists and a single consensus rating was given to each of the five parameters analysed and to each diagnosis.

The commercially available Electromagnetic Articulograph AG-100 (Carstens Medizinelektronik GmbH, Germany) was used to record tongue and jaw movements along the mid-sagittal plane during speech production. The participants were given 5 minutes of speaking time before the assessment to adjust to speaking with receiver coils on their tongue and jaw. Following this, the participants were asked to read aloud syllables and sentences, all of which contained the target alveolar stop consonant /t/ and the velar stop consonant /k/ in word initial position. The target consonants were followed by the open vowel /a/ to encourage greater tongue movement, to and from the hard palate. The syllables adhered to a CV construction (e.g. /ta, ka/). They were modelled at a rate of three syllables per second, after which participants were required to repeat the syllables 10 times, at the same rate to that modelled. The sentence read 'A tarp will cover a car'. This sentence was randomly repeated 10 times within a larger list of sentences that the participants were required to read. The participants were provided with the list of sentences prior to the assessment to make certain that reading difficulties did not influence the results.

They were instructed to read the sentences aloud at a habitual rate and loudness level. While participants repeated the syllables and read aloud the sentences, their tongue-tip, tongue-back and jaw movements were recorded.

The recorded kinematic tracings were analyzed for both the timing (i.e. time lag and timing synchrony) and spatial (i.e. contribution to consonant production and inter-articulator coupling) aspects of speech movement co-ordination were analysed during consonant production to determine any differences between the TBI and control group. The EMA analysis programs, Tailor and Emalyse (Carstens Medizinelektronik GmbH, Germany) along with custom written MATLAB functions were employed for analysis.

The results of the study revealed that group measures of time lag during real word productions indicated that the control participants and the individuals with TBI initiated tongue-tip movement prior to jaw movement during the approach phase of /t/. In both the control group and TBI group, tongue-tip movement, on average, preceded and reached maximum velocity prior to jaw movement during the approach phase of /t/. These observations are consistent with theories of motor control that are based on neuromotor synergies. Neuromotor synergies impose constraints on the timing or patterning of the potential degrees of movement freedom, to simplify the overall motor control mechanism. Thus, synergies promote a degree of efficiency in the motor system.

The authors conclude that the analysis of the individual participant data revealed differences in articulatory order (i.e. timing disturbances) and in jaw contribution to /t/ (i.e. spatial disturbances) during real word productions. With regard to articulatory order, tongue movement preceded jaw movement during the approach phase of /t/ in seven of the nine control participants, yet in only three of the nine participants with TBI. In terms of spatial co-ordination, three of the nine individuals with TBI exhibited a greater range of jaw movement compared to their matched control group. In addition, participants 2 and 8, who were identified as having severe articulatory disturbances, exhibited the most variable time latencies and utilised a greater range of jaw movement during /t/ productions. Thus, disturbances in timing and spatial co-ordination could be considered partly responsible for the imprecise speech exhibited by these individuals with TBI.

Murdoch, Justine and Gooze (2003) aimed to investigate the articulatory dynamics in children with dysarthria using a kinematic paradigm. The authors incorporated EMMA to look into the motoric disturbances exhibited in tongue movements of children with dysarthria by measuring movement speed and accuracy. The authors hypothesized that by analyzing the motor patterns of articulators using a kinematic paradigm was a more direct approach to disclose the nature of dysarthric speech.

The study involved 4 children with dysarthria following traumatic brain injury (TBI) in the age ranges of 12.7 to 17.7, the control group consisted of age and gender matched normal children with no history of speech, language or neurological conditions. The participants from both the groups repeated iterations of /t/, /s/, /k/ in VC or CVC construction and these were recorded kinematically using articulograph AG – 100. These recordings were analyzed for parameters such as distance, duration, maximum velocity and maximum acceleration. Using these kinematic parameters measures of approach phase and release phase, the approach phase was analyzed for consonant articulation and release phase for vowel articulation.

Results of the study revealed that the average movement trajectories for dysarthric group was highly variable compared to that of the control group. Further visual inspection of the trajectories of TBI children revealed increased word duration, consistent with the deviant perceptual speech feature, reduced rate of speech and phoneme prolongation. The consonant approach phase durations were significantly longer than the control group, indicating that these children's consonant productions may have contributed to the perception of increased word duration. Authors report that different articulatory mechanisms may be implemented by each child in the TBI group. The authors conclude on highlighting the benefits of EMMA in providing insights into nature of articulatory disturbances exhibited by children with dysarthria. They stress on the need for individual treatment goals for each case instead of a generalized treatment approach.

Gooze, Murdoch, Theodoros and Stokes (2000) aimed to study the EMMA investigations of the accuracy and speed of tongue movements generated by an individual with dysarthria subsequent to a severe TBI during the speech production. For the purpose, one male subject with persistent mild spastic – ataxic dysarthria subsequent to TBI was considered for the study. The subject was 19 years old and had sustained a severe TBI in a railway accident. A neuro – typical adult male with typical speech, language and hearing abilities, aged 26 years served as a control subject for the study. Articulatory assessment was carried out using two perceptual assessments and EMMA. The perceptual assessment scales included the Assessment of Intelligibility in Dysarthric Speech (ASSIDS) and a speech sample analysis.

Both the subjects were instructed to read aloud 50 randomly selected words and 22 randomly selected sentences varying in length from 5 to 15 words. The subject's productions were tape recorded and later transcribed by two experienced SLPs. For the purpose of physiological assessment, EMMA AG – 100 was used. The point of interest of the authors were the tongue tip, tongue body, tongue dorsum. The perceptual analysis of TBI subject's speech sample identified mild consonant imprecision. Vowel precision and length of phonemes were judged to be within normal limits. Quantification of the TBI subject's intelligibility level and rate of speech were carried out using the ASSIDS. Single word and sentence productions were judged to be 87% and 98.61% intelligible, respectively. Speaking rate was calculated to be 166 words per minute.

Kinematically, the averaged movement trajectories exhibited by the TBI subject and the control subject for each consonant produced revealed several differences. During the approach phase of the alveolar stop /t/ production, the TBI subject's tongue tip/blade (i.e. principal receiver coil) did not reach a high maximum velocity as the control subject. Rather, the maximum velocity (163.06 mm/s) was calculated to be 1.7 standard deviations (SD) below the maximum velocity reached by the control subject. The TBI subject's tongue tip/blade accelerated at a rate that was within 1 SD of the control subject's mean. However, the mean maximum deceleration value calculated for the TBI subject was 3.26 SD below the control mean. Whilst the distance travelled by the TBI subject's tongue tip/blade was consistent with the control subject, the mean length of time taken for the TBI subject' s tongue tip/blade to travel this distance was greater (1.71 SD) than for the control subject.

The TBI subject's tongue tip/blade in the production of /s/ reached maximum deceleration during movement up to the palate, resulting in a distinct point being reached at (or at least near) the palate. The position at the palate was not maintained, however, like the control subject. This again could be viewed as indicative of disturbance in the cerebellum's predictive function, as the TBI subject may not have been able to accurately gauge the distance to be travelled up to the point of intent, his tongue decelerating too early and, subsequently, unable to remain at the palate for a length of time. The shorter length of time in which the TBI subject's tongue was close to the palate did not translate into perceptual judgments of consonant imprecision or reduction, however, as could have been anticipated. Rather the phonetic transcriptions of the TBI subject's productions of /s/ suggested that the consonant had been produced correctly.

The TBI subject was able to accelerate his tongue as quickly as the control subject in the production of the alveolar fricative /s/ and, in contrast to the production of /t/, decelerated as quickly as the control subject, and reached a maximum velocity that was consistent with the control subject. Perhaps the longer distance travelled by the TBI subject's tongue tip/blade during the approach phase of /s/compared to the control subject and also in comparison to his own production of/t/, provided sufficient acceleration time for the high velocity to be reached and provided adequate time for deceleration to occur prior to reaching the palate. This early deceleration, in addition to the longer distance travelled, would have contributed to the increased duration of the approach phase for /s/.

In the approach phase of velar stop /k/ production, the control subject reached maximum deceleration close to the palate, with the back portion of the tongue being held in position at (or at least close to) the palate for a period of time, as evidenced by the plateau in the y-position profile. During this plateau period, themed-portion of the tongue and the tongue tip/blade continued to move up towards their spatial endpoints and then down again. After the tongue tip/blade and importation of the tongue started to move down, the back portion of the tongue followed in the release action, tracing a rounded trajectory down from the palate. The TBI subject's production of the velar stop /k/ involved the back portion of the tongue reaching maximum deceleration on the approach up to the palate, with a distinct endpoint position being reached, but not held as evidenced on the position profile. Again, as in the production of /s/, the early deceleration may have been instrumental in reducing the length of time that the tongue remained at the palate. It was noted that all three receiver coils on the TBI subject’s tongue traced similar movement trajectories and reached their approach phase endpoints simultaneously, unlike the control subject’s receiver coils. This movement may reflect limited flexibility between the two suggested functionally independent components of the tongue, the tip-blade and tongue body. This limited flexibility, in turn, may be indicative of excessive tone or hypertonicity in the tongue.

These existing literatures have used varied methodologies to tap on motor equivalence, however the very nature and its manifestation is poorly understood.

Chapter – III

Method

Study design: The present study incorporated a ***standard group comparison*** where the participants (clinical group and the controls) were selected on the basis of convenient sampling method. Further, the study adopted ‘subject matching’ strategy, where every available atypical (clinical) participant was compared with age and gender matched neuro typical (normal) control.

Participants

The participants were included in the study after obtaining their written informed consent. All ethical procedures were followed. The following were the inclusion criteria common to both clinical and control groups of the present study;

- All participants were ensured that they have good comprehension to follow the instructions of the tasks involved in the study.
- It was ensured that they are mentally alert and have no decrease in the level of consciousness.
- Participants had no systemic illness at the time of testing.
- Participants had no artificial dentures, sores in the mouth or lips or any other oral pathology at the time of testing.

Group 1 (clinical group): consisted of 4 (2 males and 2 females) atypical individuals in the age range of 20 to 50 years (mean age = 33.3 years), with clinically documented articulatory deviations secondary to dysarthria. Demographic details and major complaints secondary to dysarthria have been summarized in table – 1. This group included individuals with dysarthria, further, the participants were included in this group based on the following inclusion criteria;

- Provisionally diagnosed as dysarthria which is confirmed by Frenchay Dysarthria Assessment (FDA) (Enderby, 1983) and a neurologist, according to the standard protocols of the Diagnostic section, Department of Clinical Services, All India Institute of Speech and Hearing (AIISH), Mysuru.
- Cognitive impairments were ruled out using MMSE (Folstein et al, 1975). Only those individuals with a score of more than 23 were included.
- No visual or auditory deficits as confirmed by an informal screening.
- No psychological issues such as depression, apathy etc as ruled out by a psychologist.

Table - 1: Showing demographic and clinical details of participants in Group - 1.

Subject	***Age /Sex***	***Major Complaint***	***Neurological findings***	***Provisional Diagnosis***
S1	63.5/ M	Reduced speech intelligibility, Loss of sensation on right side of face.	(?) CVA	Flaccid Dysarthria
S2	28 / F	Reduced speech intelligibility, Difficulty and pain during swallow.	(?) CVA	Flaccid Dysarthria
S3	19 / F	Reduced speech intelligibility, Inability to raise the loudness of voice.	Idiopathic	Spastic Dysarthria
S4	23 / M	Reduced speech intelligibility, Inability to maintain loudness of voice and difficulty in swallowing liquids.	TBI	Hypokinetic Dysarthria

Group 2 (control group): included 4 (2 males and 2 females) typical individuals in the age range of 20 to 50 years (mean age = 33.3 years). These participants were selected on the basis of age and gender matching to that of available clinical group. Further these participants had no history of neurological, metabolic and systemic disorders (hypertension and diabetes mellitus), cognitive, linguistic and behavioural deficits, speech, language and hearing problems, structural and/or functional abnormalities in the oral structures and use of artificial dentures. Those without a history of the above were selected.

Assessment Procedures

All the participants in group - 1 underwent routine speech, language and hearing evaluation as per the standard protocols of the department of clinical services at AIISH, Mysuru. The standard protocols included, a detailed case history, Oral Peripheral Mechanism Examination (OPME), Neurological evaluation by a consultant neurologist, dysarthria evaluation; that included administration of FDA (Enderby, 1983).

EMMA assessment

The commercially available Electromagnetic Articulograph AG- 501 (Carstens Medizinelektronik GmbH, Germany) was used to record tongue, lips and jaw movements along the mid-sagittal plane during speech production. EMMA was chosen as it is capable of measuring articulatory movements simultaneously, allowing speech movement co-ordination to be investigated and it has been proven to be a safe, non-invasive and reliable technique for recording articulatory movements during speech.

It is a motion capture system which is specifically designed to track the real-time articulatory oro-facial movements as a non – line off sight motion capture system. The instrument is specifically designed to track speech related articulatory orofacial movements and articulatory kinematic plots in three dimensions of space: The x, y, and z axes correspond to the medial-lateral, inferior-superior, and posterior-anterior directions, respectively (Ji, Johnson & Berry, 2012). The present study utilized the capabilities of an articulography to capture 3 - dimensional data with respect to spatial and temporal domains of a movement. These movements are dynamic in nature which provides better visualization as well as spatio – temporal representations of speech.

Instrumentation and method of measurement

Set up and environment*:* The data recording was carried out in a quiet laboratory setting and data from each participant was collected individually. A noise free environment with adequate lighting and ventilation and minimal distractions in the environment was ensured. The entire procedure of data recording was carried out in following stages;

1. ***Calibration of the instrument*:** AG 501 along with the 8 test sensors (2 reference and 6 test sensors) were calibrated as specified by the prescribed procedure of the manufacturers (Carstens Medizinelec- tronik, Lenglern, Germany) before collecting data from each participant (Figure - 1)

Figure 1: Showing calibrated instrumental setup of AG 501.

2. ***Instrumental set up***: Once the sensors (test sensors and the reference sensors) were calibrated as depicted in figure - 1, each participant was tested individually by making him/her to sit comfortably within the electromagnetic cubicle of the AG 501, as shown in figure – 2 below.


[redacted]

Figure 2: Showing the participant seated within the electromagnetic field of the articulography.

3. ***Sensor placement:*** Once the participant was comfortably seated below the transmitters of the articulograph, two reference sensors were placed on the right and the left mastoid respectively. One sensor was placed on the forehead, which served as head correction marker. The five remaining sensors were placed accordingly, two sensors on the tongue, one on tongue tip (TT) and the other on tongue body (TB). One sensor each was placed on upper lip (UL), lower lip (LL) and jaw (J) respectively. Further, these were secured firmly in the point of interest using an epi - glue adhesive and biotape. The entire set of sensor placement is depicted in figure - 3.

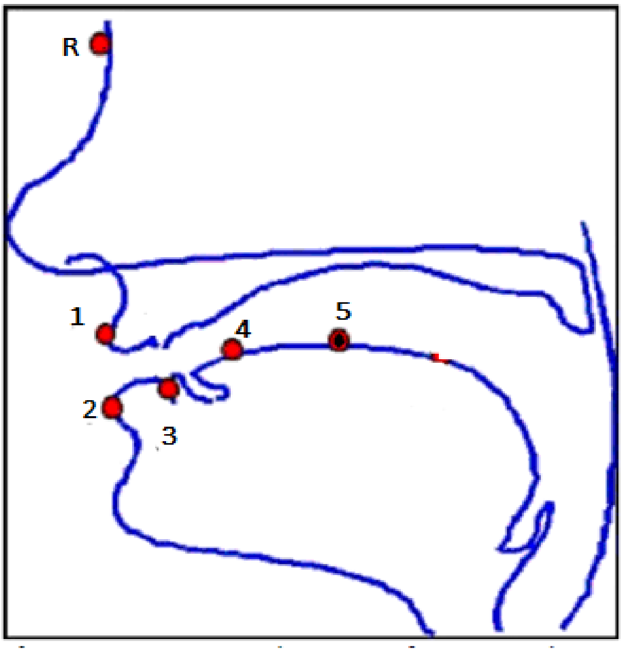


Figure 3: Schematic representation of sensor placement at 1(UL), 2(LL), 3(J), 4(TT), 5(TB) and R (Reference).


[redacted]
[redacted]

Figure 4: Actual placement of test sensors on a subject at points of interest.

Recording procedure: Before the commencement of actual recording, the participants were given 5 minutes of speaking time to adjust their speaking with receiver coils on their tongue, lips and jaw. Following this, the participants were asked to converse with the investigator to retain the naturalness of speaking with the attached sensors. The entire recording procedure was carried out in following stages as described under the following headings;

1. ***Stimuli and instruction:*** The participants were required to utter the V-C-V combinations of /aʧa/, /at̪a/ and /aʈa/ along with a carrier phrase “I am saying”. Stimuli were randomized across participants and utterances. They were instructed to utter the target stimuli ten times as 'clearly as possible’.

2. ***Recording of the data*****:** Before the actual recording the investigator created an individual file for each of the participant within the AG 501 control unit, where each of the recorded files was saved. Once an individual file was created and the control window had been set to ‘real time display’ the participant received the start command from the investigator. Upon successful recording, each individual file was saved for further extraction and analysis.

Extraction of EMMA data: The successfully recorded data was extracted using ***Visartico software*** (Ouni, Mangeonjean& Steiner, 2012). It is a freeware that facilitates articulatory data visualization and extraction. It provides visual information of the data in 3D spatial view, midsagittal view, and temporal view (As shown in figure - 3). This was used to extract the kinematic data by specifying the sensor orientations and the corresponding data was extracted in terms of time (s), displacement of y and z axes (mm) and their corresponding velocity data (cm/s). These extracted sensor specific data was used for further analysis.

Figure 5: Showing a working interface of visartico used for EMMA data extraction

EMMA data analysis procedure: Once the sensor specific EMMA data was extracted, they were subjected to analyses procedures with respect to the aims and objectives of the study as mentioned in the following sections. For all the analyses, a custom written MATLAB (The Mathworks of Natick, Massachusetts, USA) program called SMASH (Speech Movement Analysis for Speech and Hearing research) (Green et al., 2013) was used.

Measures of stability: One of the aims of the present study was to investigate the stability and variability of articulatory dynamics among individuals with dysarthria as compared to that of age and gender matched neuro - typical individuals. For this purpose, two kinematic measures, Spatio - temporal indices (STI) and Velocity profiles were considered.

The STI is defined as the sum of standard deviations of kinematic waveforms from multiple repetitions of an utterance, which are time and amplitude normalized (Smith et al., 1995). Whereas the velocity profile of movements is a time domain graph of articulatory movement. When these two measures are considered across production conditions in which the spatial and temporal dimensions of movements are varied, that provide information about the variable motor control that exists between productions (Hogan, 1984; Nelson, 1983).

Measures of coordination: Green, Moore, Higashikawa and Steeve (2000) introduced two new analysis techniques called the ‘spatial coupling’ and ‘temporal coupling’ to study the coordination between the articulators. This measure is a function of cross correlation between kinematic traces of any two articulators of interest. When two articulatory trajectories are in considered in a cross - correlation function, it measures the 'lead' and 'lag' values of each articulatory movement with respect to each other. The peak coefficients associated with each lead and lag values would provide a window to estimate the degree of temporal and spatial coupling during the act of inter - articulator coordination.

Temporal coupling: was measured through the **movement onset time (MOT)** (see Figure 6) It is a calculation of the time lag between the movement initiation of any two articulatory points of interest. For example, the time lag between the initiations of tongue movement to the initiation of jaw movement during productions of any particular sounds of interest (see Equation 1).This measure would indicate a quantitative representation of motor equivalence.

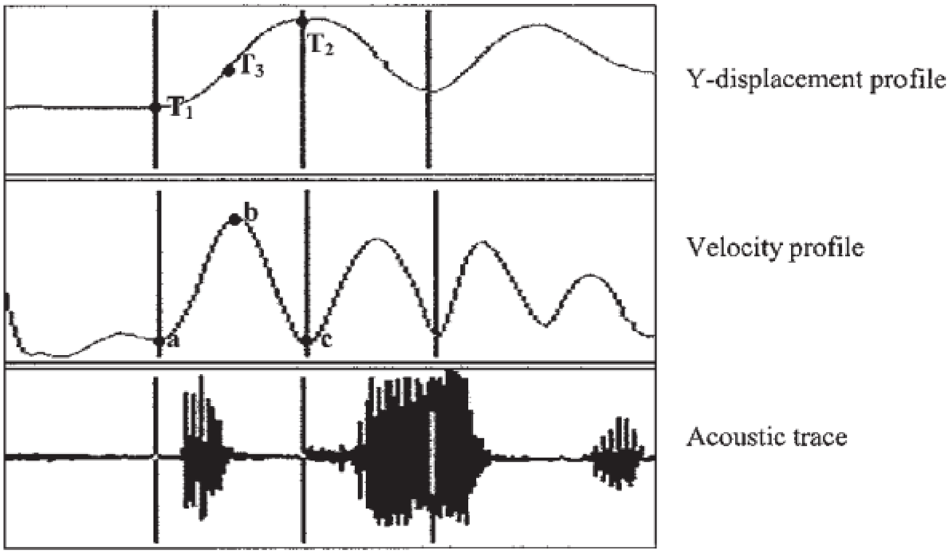


Figure 6: Example y – axis displacement and velocity profiles, displaying onset of velocity (a), movement onset time (T1), maximum velocity (b), time of maximum velocity (T3), minimum velocity (c), end of approach phase (T2), and duration of approach phase [5 (T2 – T1)];

Equation (1)

$$\text{Time lag (MOT)} = 5 * (\text{T1}_{\text{(Tongue)}} - \text{T1}_{\text{(Jaw)}})$$

A negative lag value indicated that tongue-tip movement was leading jaw movement and a positive lag value indicated that tongue-tip movement was lagging jaw movement. A lag value close to zero would indicate high degree of synchrony. The above - mentioned equation (1) was written in MATLAB file format and all the analyses were carried out within the MATLAB environment. Peak coefficients (negative or positive) and their associated lags were derived from the cross - correlation functions computed between the treated displacement traces of all possible articulatory pairs (TT, TB and J).

Spatial coupling: Spatial information was also obtained from the y-displacement graphs produced using SMASH. From these graphs, the direction of tongue and jaw movement (i.e. upwards or downwards) during the production of target stimuli was determined. Descriptive comparisons were made between the Dysarthric and control group to determine any differences in the spatial coordination of articulatory movement.

Once the mentioned measures of variability and coordination were obtained as described in earlier section, these were subjected to appropriate statistical treatment. The results are presented in the following chapter.

Chapter – IV

Results

The present study was proposed to analyze and compare stability, variability and inter – articulatory coordination for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501. With respect to the specific objectives of the study following statistical procedures were employed.

1. The first objective of the study was to analyze and compare movement stability and variability of articulatory dynamics in terms of STI for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501.

   Shapiro Wilk's test of normality was carried out for group level STI data, which did not reveal a standard normal distribution at $p>0.05$. Since the data did not follow standard normal distribution non – parametric Mann Whitney U test was used.

2. The second objective of the study was to investigate inter articulatory coordination as measured on spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501.

   For the above mentioned objective, the temporal coupling data was subjected to Shapiro Wilk's test of normality. The results of the test revealed that the group level data did not follow standard normal distribution. This necessitated to subject the group level temporal coupling data using non – parametric Mann Whitney U test for further statistical analysis.

Descriptive statistics was used to obtain mean, median and standard deviation of STI and temporal coupling across both the groups. The respective means and medians were subjected to above mentioned statistical treatment and the results have been presented under following headings.

Comparison of stability and variability across normal and dysarthric individuals

From the visual inspection of the STI data depicted the table 1, it is evident that dental sound /t̪/ has the least STI values among the three group of sounds used as stimuli for the present study. It was followed by palatal and retroflex sounds, which had the highest STI values among the normal group. These data reflect that dental sounds are most stable as reflected through least STI values whereas retroflex sounds are the most variable. Further, when the three articulatory point of interest was compared across three groups of sound, interesting findings were revealed.

Table 2:

Mean, median and standard deviations for the STI values obtained for normal individuals across the stimuli of / t̪/, /ʈ/ and / ʧ /

	Normal Group								
	t̪			ʈ			ʧ		
	TT	TB	JAW	TT	TB	JAW	TT	TB	JAW
Mean	25.57	26.81	25.12	26.46	26.57	26.10	26.31	26.49	27.11
Median	25.63	26.54	24.63	26.45	26.475	26.285	26.735	26.745	26.905
SD	1.08	1.09	1.38	1.237	1.84	0.98	0.88	1.77	0.9

Note: TT = Tongue Tip, TB = Tongue Body, SD = Standard Deviation

Across all the three articulators, JAW had the least STI value, indicating that JAW may be the most stable articulator. For the dental sound /t̪/among the three articulatory points of interest, JAW has the least STI which was followed by TT and the highest STI value was observed for the point of TB. Similarly, when a retroflex /ʈ/ was considered, the least STI value was observed for JAW which was followed by TT and the highest STI value was observed for TB. When a palatal sound /ʧ / was analyzed, it was found that TT had the least STI which was followed by TB. Looking at the trends in STI data across sound class and articulatory point of interest, it can be inferred that dentals have least STI, which are followed by Palatals whereas Retroflex sounds have the highest STI. Among the articulatory points of interest, JAW had the least STI followed by TT and TB.

Table 3:

Mean, median and standard deviations for the STI values obtained for dysarthric individuals across the stimuli of / t̪/, /ʈ/ and / ʧ /

	Dysarthric Group								
	t̪			ʈ			ʧ		
	TT	TB	JAW	TT	TB	JAW	TT	TB	JAW
Mean	37.03	35.22	35.41	34.71	35.15	34.06	33.41	33.26	33.5
Median	36.9	35.73	35.56	34.14	35.31	33.63	33.48	33.06	33.71
SD	1.27	2.44	2.02	1.85	2	2.12	0.61	1.4	0.67

Note: TT = Tongue Tip, TB = Tongue Body, SD = Standard Deviation

From the visual inspection of the STI data of dysarthric individuals depicted the table 2, it is evident that palatal sound /ʧ/ has the least STI values among the three group of sounds used as stimuli for the present study. It was followed by retroflex and dental sounds, which had the highest STI values among the normal group. These data reflect that palatal sounds are most stable as reflected through least STI values whereas dental sounds are the most variable. Further, when the three articulatory point of interest was compared across three groups of sound, interesting findings were revealed. Inspection of STI data from the dysarthric group depicted in table 2, did not follow any trends of sound class or articulatory points of interest that were observed in the normal group.

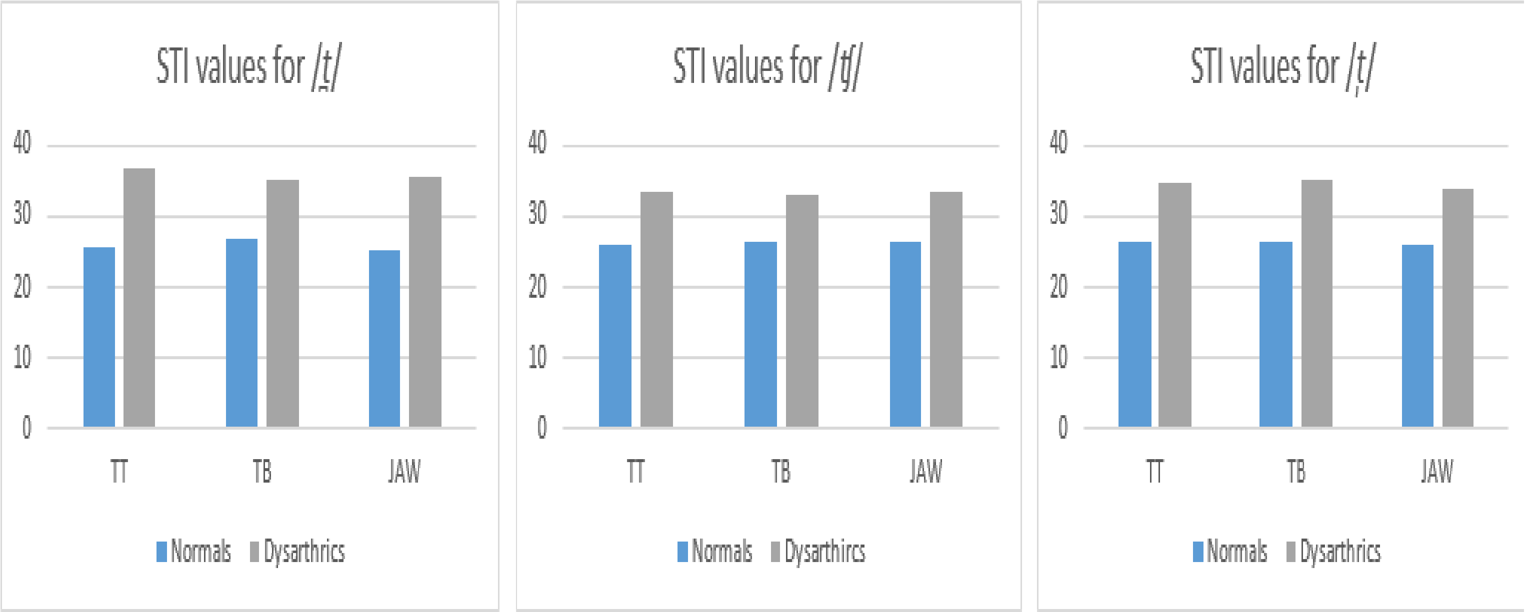


Figure 7: Showing graphical representation of STI values across groups for dental sound (left pane), palatal sound (middle pane) and retroflex (right pane).

The comparison across the groups of normal individuals and dysarthirc individuals have been depicted in Fig 7. The groups have been compared across class of sounds used in the present study. When comparison across groups were made, the STI data did not follow standard normal distribution, Hence the data was subject to non parametric statistical verification. Mann

Whitney U test revealed a statistically significant difference between for TT (Z=|2.3|; p=0.029), TB (Z=|1.15|; p=0.02) and JAW(Z=|2.3|; p=0.029).

Comparison of temporal coupling between normal and dysarthric individuals

The second objective of the study was to investigate inter articulatory coordination as measured on spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501.The descriptive statistics across groups for the temporal coupling data have been depicted in the following section.

Table 4:

Mean, median and standard deviations for the temporal coupling values obtained for normal individuals across the stimuli of / t̪/, /ʈ/ and / ʧ /

	Normal Group								
	/t̪/			/ʈ/			/ʧ/		
	T-B	B-J	T-J	T-B	B-J	T-J	T-B	B-J	T-J
Mean	0.91	-0.36	-0.03	0.92	-0.22	-0.27	0.94	-0.24	-0.26
Median	0.93	-0.34	-0.05	0.91	-0.38	-0.53	0.94	-0.43	-0.46
SD	0.08	0.14	0.57	0.02	0.45	0.49	0.03	0.45	0.47

Note: T-TB = Tongue Tip -Tongue Body, B-J = Tongue Body – Jaw, T – J = Tongue Tip –Jaw, SD = Standard Deviation. Negative values indicate a lag condition.

Table 5:

Mean, median and standard deviations for the temporal coupling values obtained for dysarthric individuals across the stimuli of / t̪/, /ʈ/ and / ʧ /

	Dysarthric Group								
	/t̪/			/ʈ/			/ʧ/		
	T-B	B-J	T-J	T-B	B-J	T-J	T-B	B-J	T-J
Mean	0.95	-0.25	-0.57	0.95	-0.03	0.22	0.95	-0.24	-0.33
Median	0.95	-0.46	-0.57	0.95	-0.04	0.43	0.96	-0.43	-0.58
SD	0.02	0.4	0.01	0.02	0.59	0.43	0.03	0.45	0.52

Note: T-TB = Tongue Tip -Tongue Body, B-J = Tongue Body – Jaw, T – J = Tongue Tip –Jaw, SD = Standard Deviation. Negative values indicate a lag condition.

The temporal coupling values depicted in table 4 and 5 indicated that on average, tongue-tip movement preceded jaw movement across all three sounds. In the control group, participants, on average, initiated tongue-tip movement prior to initiating jaw movement. It should be noted, however, that there was a high degree of variability within both the control group and the dysarthric group. These results indicated that tongue-tip movement did not consistently lead jaw movement across sounds used in the present study.

Before subjecting these findings to statistical verification, they were tested for normal distribution using Shapiro – Wilks test of normality. The data however was not normally distributed, this necessitated the use of non - parametric Mann Whitney U test for further statistical verification. The results of the Mann Whitney U test revealed a statistically significant difference between T-B (Z=0; p=0.02)., T-J (Z=|2.3|; p=0.029) but not for B-J (Z=|2.3|; p>0.05).

Comparison between spatial coupling across normal and dysarthric groups

The other objective of the study was to investigate spatial coupling between the articulatory points of TT, TB and JAW. The following are the descriptive results on how each point of articulators interacted with each other across the production of stimuli used in the study.

Spatial coupling for the production of /ʧ/ across the groups of normal and dysarthric individuals

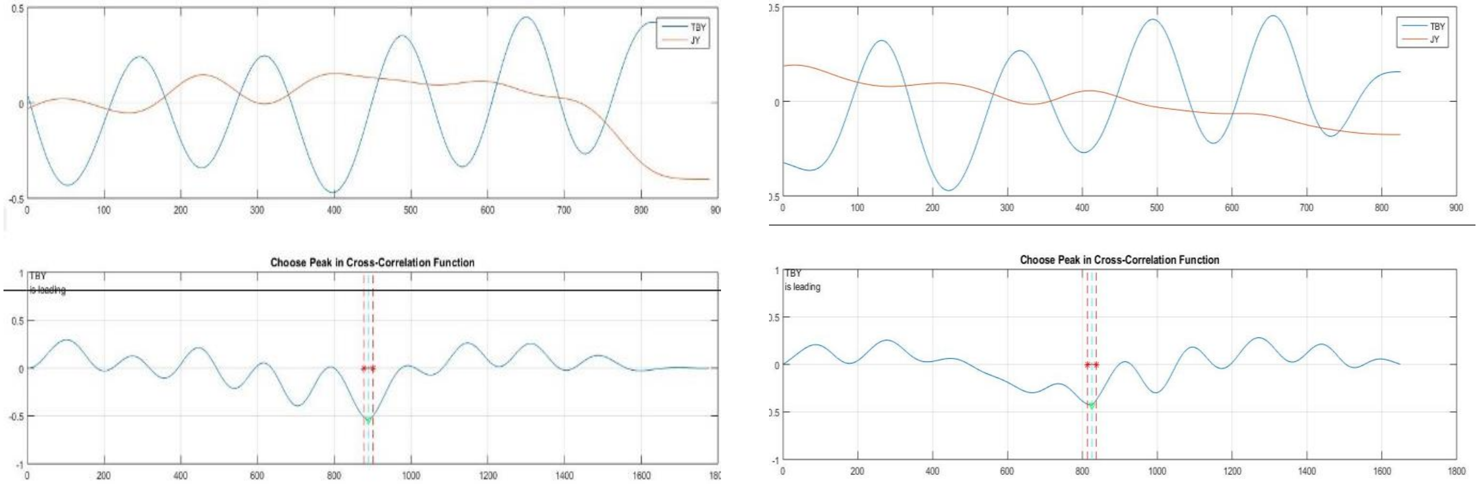


Figure 8: Showing inter articulatory coupling between tongue body – Jaw for ***/ʧ/ sound* -** normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for Jaw & Blue lines – Electrode recordings for tongue body)

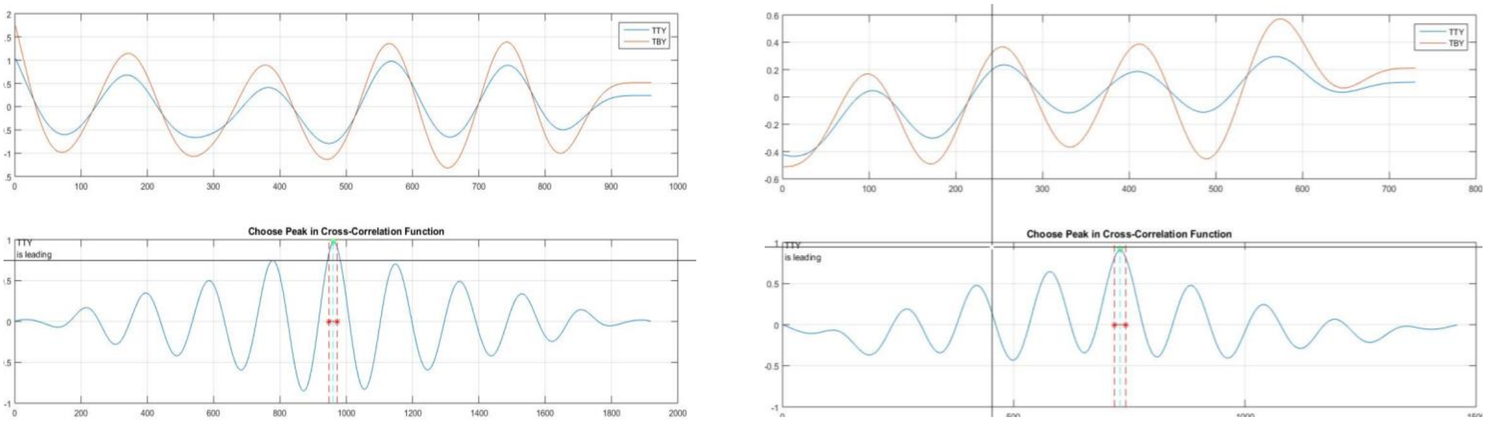


Figure 9: Showing inter articulatory coupling between tongue tip – tongue body for ***/ʧ/ sound*** - normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for tongue body & Blue lines – Electrode recordings for tongue tip)

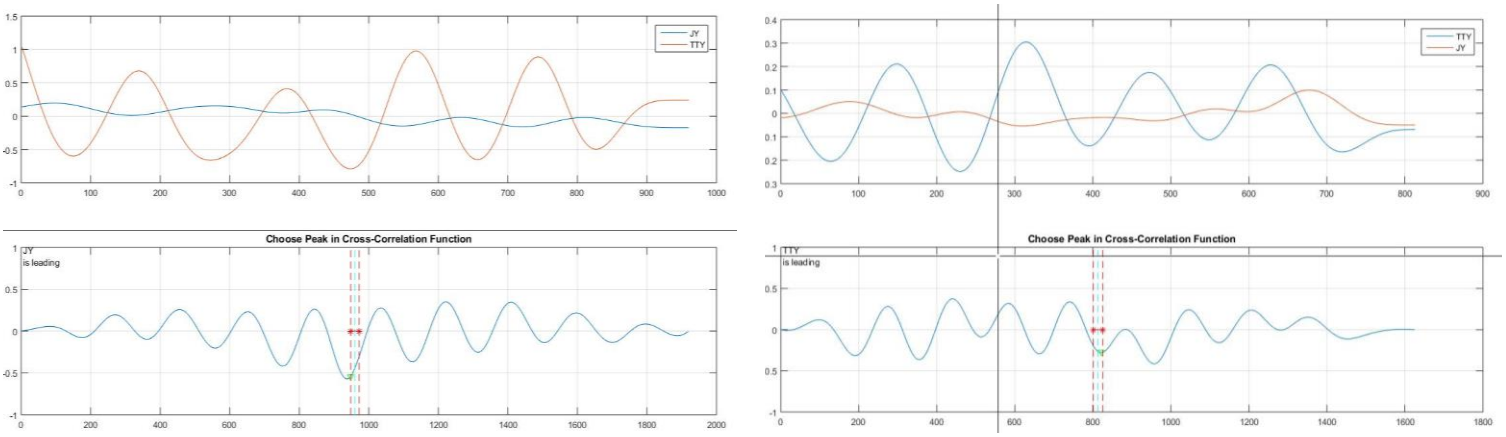


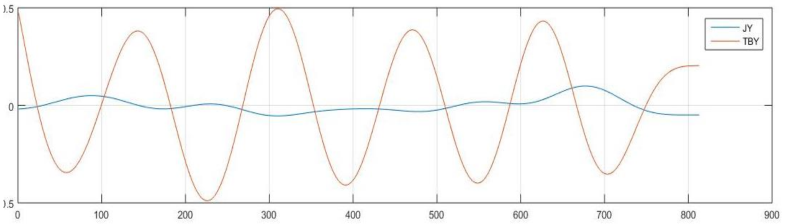
Figure 10: Showing inter articulatory coupling between tongue tip – jaw for ***/ʧ/ sound -*** normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for tongue tip & Blue lines – Electrode recordings for jaw)

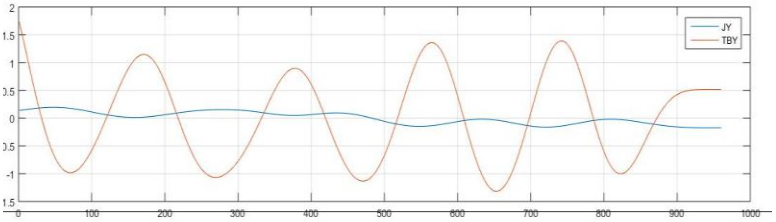
In Figures 8, 9 and 10, the articulatory target /ʧ / was influenced by the preceding vowel /a/. Even through visual inspection, there did not appear to be a notable difference between the control group and the dysarthric group finer observations revealed several interesting findings.

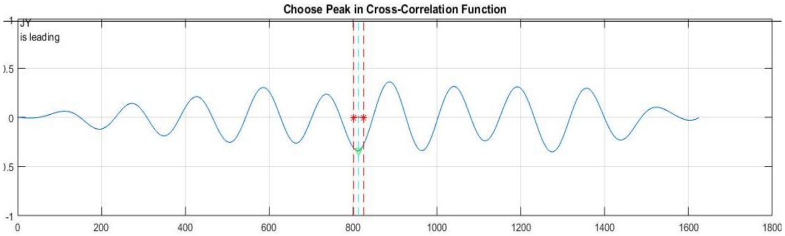
On all but two occasions he initiated tongue-tip movement long before he initiated jaw movement. The tongue-tip reached two prominent peaks, one before and one after the jaw reached its peak; the jaw was in a low position when the tongue-tip reached its first peak. The jaw movement for normal individuals was upward for the open-mid vowel and then moved downward to produce the open vowel. However, in the dysarthric group the tongue-body also moved upward during the production of /a/, before moving upward for /**ʧ**/.

Further inspection reveals that that the time taken for iterations of /**ʧ**/ by the dysarthric group was longer (8 seconds) compared to that of normal individuals (6.5 seconds). When compared to the normal individuals the dysarthric group wave morphology is consistently poor across all articulatory points of interest. Interestingly, however, the phasic movements are preserved with good co - ordination in the movements between the three articulators.

Spatial coupling for the production of /ʈ/ across the groups of normal and dysarthric individuals







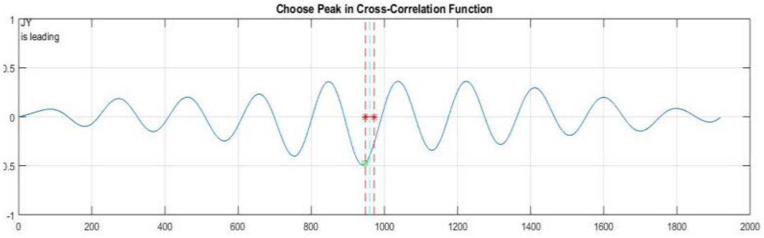


Figure 11: Showing inter articulatory coupling between tongue body – Jaw for ***/ṭ/ sound -*** normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for tongue body & Blue lines – Electrode recordings for jaw)

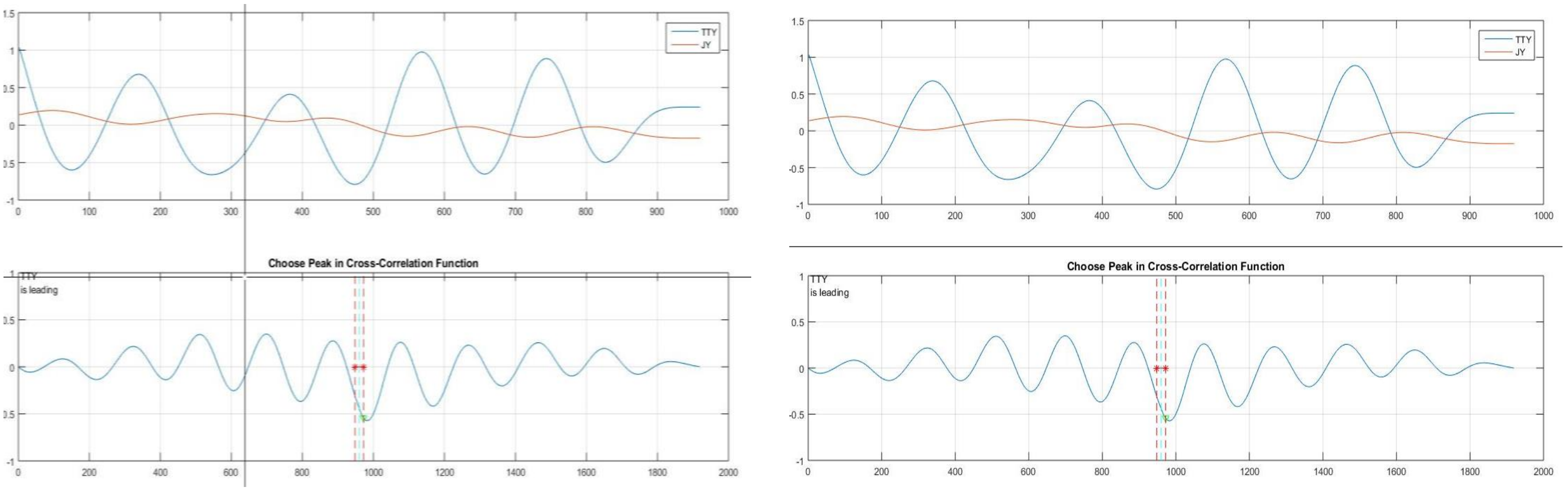


Figure 12: Showing inter articulatory coupling between tongue tip –jaw for ***/ṭ/ sound -*** normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for jaw & Blue lines – Electrode recordings for tongue tip)

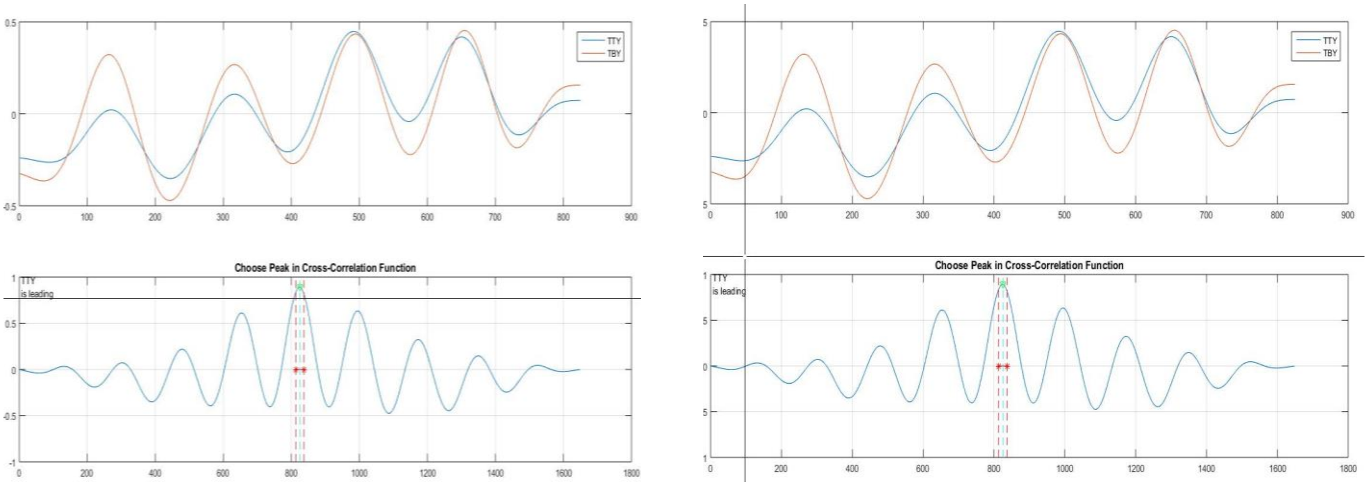


Figure 13: Showing inter articulatory coupling between tongue tip – tongue body for ***/ṭ/ sound-*** normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for tongue body & Blue lines – Electrode recordings for tongue tip)

The Figures 11, 12 and 13 reveal that the production of */t̩/* was longer in the dysarthric group compared to that of normal individuals. In the control group, good wave morphology and coordination for the cognate articulators were evident. In contrast, in the dysarthric group, it was observed that the morphology was good only for the tongue tip and tongue body coordination compared to the other articulatory sets.

Spatial coupling for the production of /t̪/ across the groups of normal and dysarthric individuals

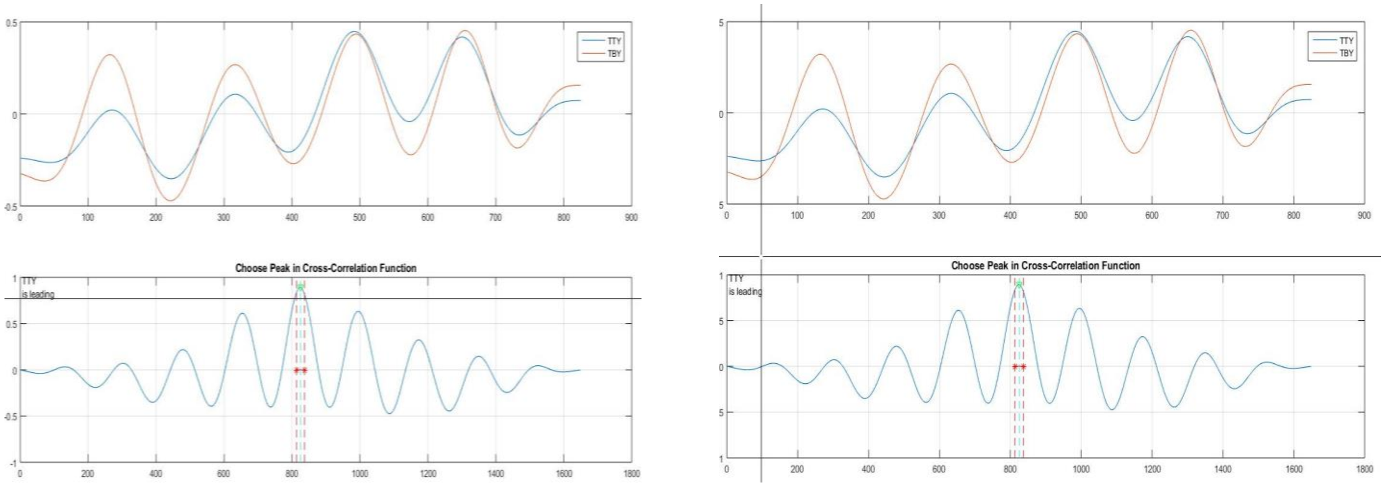


Figure 14: Showing inter articulatory coupling between tongue tip – jaw for ***/t̪/ sound*** - normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for jaw & Blue lines – Electrode recordings for tongue tip)

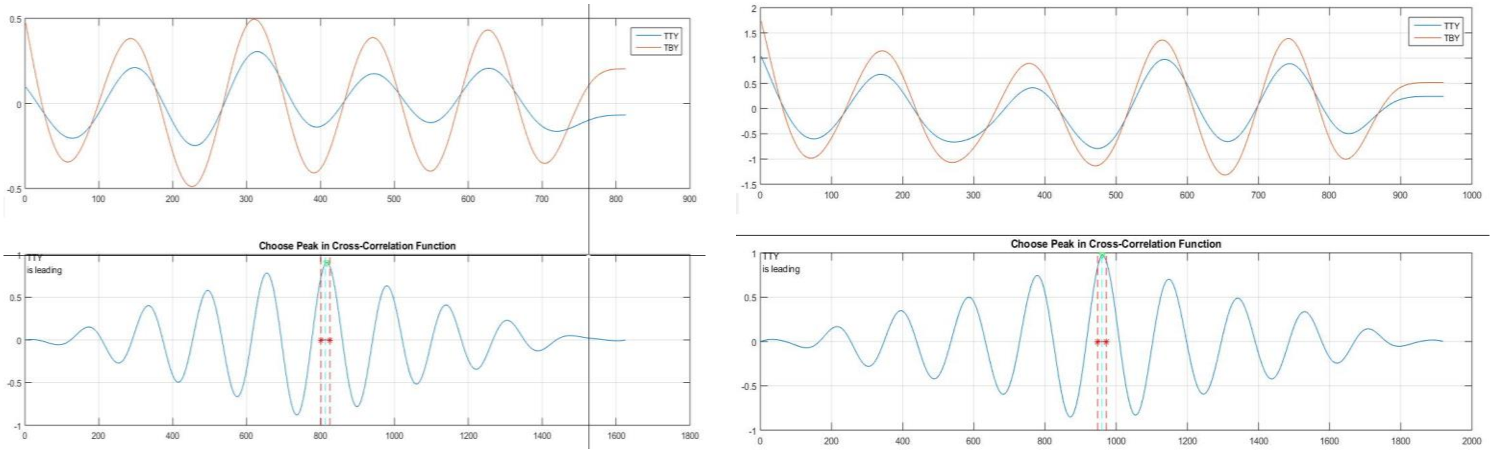


Figure 15: Showing inter articulatory coupling between tongue body and tongue tip for ***/t̪/ sound*** - normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for tongue body & Blue lines – Electrode recordings for tongue tip)

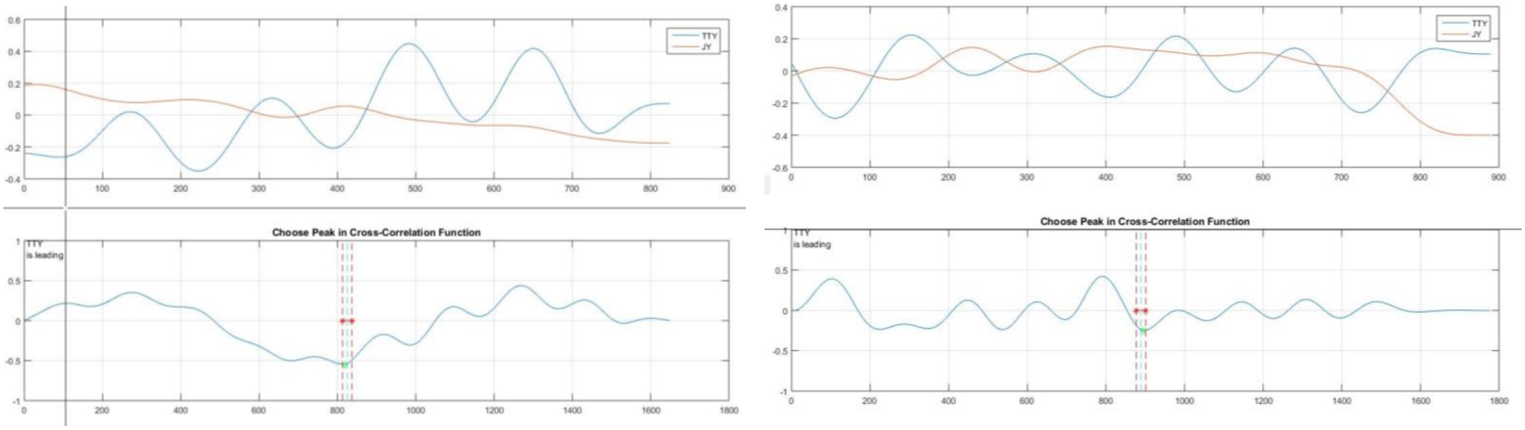


Figure 16: Showing inter articulatory coupling between tongue tip – jaw for ***/t̪/ sound*** - normal individual (left pane) and dysarthric individual (right pane) (Red lines – Electrode recordings for jaw & Blue lines – Electrode recordings for tongue tip)

The Figures 14, 15 and 16 reveal that the spatial profile of the TT, TB and JAW were not in phase and this was also reflected in lack of coordination between these articulators. Some interesting points emerged, as seen in the dysarthric group wherein the TB and JAW did not show good peaks but the TT – TB movements were relatively preserved to represent the iterated movements. Overall, the results point to increased duration in the dysarthric group with duration being more than that of normal individuals. In terms of wave morphology, majority of the participants from both groups showed good wave morphology with preserved peaks. These interesting findings are discussed and elaborated in the next section.

Chapter V

Discussion

The aim of the present study was to compare STI, spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501. The findings of the study which were presented in the previous results chapter are discussed in the following sections below.

Comparison of Spatio Temporal indices across the groups

The spatio-temporal indices reflect the control integrity of the effectors across spatial and temporal domain for a given movement. Ideally, a stable motor system would be a value less than a unit, if and only when the coordinative movements of given set of articulators are in phase performed within an expected time frame. In case of conditions like dysarthria which is considered as a disorder of coordination, these STI values vary significantly. These variations in the STI values reflect the in-coordination present in dysarthric individuals,

From tables 1 and 2, it can be observed that stability was higher in the normal individuals, indicating that a normal motor control system is much stable compared to that of a compromised system such as in dysarthric individuals. An interesting finding within the normal group is higher across subject variability for STI values, these variations with normal group may indicate that motor strategies used across individuals is not same. It can be inferred that different individuals use different motor strategies to achieve the same motor goal.

When STI values were inspected within the dysarthric group, several idiosyncratic but interesting findings were revealed. The variations within the dysarthric group, as expected were higher than the normal individuals. Further, each individual participant in the dysarthric group exhibited different motor strategies to compensate for the disordered system. This is reflected in STI values varying across each articulatory point of interest as well as each class of sounds used as stimuli in the present study. These idiosyncratic motor behaviors may reflect the presence of motor equivalent strategies that may be used for speech production by dysarthric individuals. Analyzing these findings within the framework of motor program theory (Schmidt, 1975), we can observe a trade - off relationship in the spatial and temporal dimensions of speech in order to attain the target sound (often defined in acoustic –perceived standards of a given language). In line with this explanation, the findings from the present study reveal that, when spatial dimensions are disturbed, rescaling /compensation occurs in the temporal dimension and vice versa.

When both the groups were compared there was a significant difference in the STI values which may indicate a possible dyscoordination in the motor system of dysarthric individuals as compared to that of age and gender matched normal individuals. The presence of dyscoordination in the spatial and the temporal domains observed in the present study are in agreement with the earlier findings of Gooze, Murdoch, Theodoros and Stokes (2000) and Murdoch, Justine and Gooze (2003). Even though these studies (Gooze, Murdoch, Theodoros & Stokes, 2000; Murdoch, Justine & Gooze 2003) do not consider STI to comment about the spatial and temporal dyscoordination, their results suggest a disruption in these two domains. The present study quantifies the extent of dyscoordination numerically by the use of STI.

Comparison of spatial and temporal coordination across group

The axis of interest in the present study is the y axis, which represents the movements in the superior- inferior direction. The principle movement direction for all the stimuli considered in the present study is the superior - inferior direction and hence the traces in the y axis are very relevant to understand the motor primitive of articulatory points of interest. The dysarthric group showed an increased duration for the utterance chain compared to the age and gender matched normal individuals. This result can be attributed to the deficient neuromotor control in this group. It is not within the scope of the present study to attribute these difficulties to a particular neuromotor substrate, as the dysarthric group is not homogeneous. Further studies should consider homogeneity to better associate a cause – effect relationship.

When both groups were compared for spatial and temporal coordination for speech production, high degree of variability was observed in both the groups. An interesting finding is that the Co-articulation effects were evident and intact in both the groups. Co-articulation refers to interactive influences across articulatory targets, such that the features of one articulatory gesture may influence the attributes of a preceding or successive articulatory gesture. But the contribution of each articulatory point of interest to co - articulation was again variable; no specific sub groups of motor strategies could be identified with both groups. Since the data of the present study was idiosyncratic in nature, further findings are discussed at a case level for better understanding.

The amplitude peaks in the spatial traces of normal individuals were distinct in terms of representing the up-down movement of the TT, TB and JAW across all the iterations that were analyzed. In comparison to this, the dysarthric individuals showed poor wave morphology in terms of amplitude, which reflects on their inability to target the required range of movement in terms of amplitude for the chain of sounds selected as stimuli in the present study. These reflect a reduced spatial integrity in the execution of up-down movement displacement by TT, TB and JAW. Over and above this factor, the figures from 5 to 9 also reveal a non - phasic movement of the TB and JAW.

It is known that TT and JAW move in the same direction (upwards and downwards), to facilitate production of sounds considered in the present study. An acceptable speech sound production can occur only when the target articulators move in a phasic manner, which in turn leads to good coordinated movement for the target sound production. This is seen to be reflected well in the traces of the normal individuals but not in that of dysarthrics, where the traces indicate disturbed phasic movements and hence lack of coordination. Interestingly however, the participant 2 in the dysarthric group showed good phasic movement and this could be due to the focused articulation training the individual received during therapy.

It was also observed that the amplitude peaks of the jaw movement were comparatively distinct compared to the TT and TB which were non distinct in most of the dysarthric individuals except participant 2. This revealed that the JAW movement of gliding superiorly and inferiorly was relatively preserved, but the TT and TB which had to stretch a distance to produce the target stimuli lacked the required motor control. The mass of the JAW is higher than the TT and TB put together and hence it has lower degrees of freedom for movements resulting in a possible distorted system. These finding also suggest that the coordinate structures of tongue and jaw have struck a motor balance (motor equivalence) as required for the target production where the compensated movements of the jaw occurred to meet the lacunae in the tongue movements. It may thus be concluded that motor equivalence is attained even in the movements of dysarthric individuals, as evidenced from the results of the present study.

Interestingly, the movement traces for TT reached peak velocity earlier to that of the jaw movement in three out of four participants in the dysarthric group who initiated jaw movement prior to TT movement. Given that earlier researchers (Gooze, Murdoch, Theodoros & Stokes, 2000; Murdoch, Justine & Gooze 2003) have reported disturbances on temporal domain in tongue movements of dysarthric individuals, it could be inferred that jaw movement were initiated prior to the movements of TT in individuals with dysarthria to compensate for the delayed onset of TT movement. Furthermore, it could suggest a phasic relationship between the timing and spatial aspects of speech movement co-ordination. The JAW may have facilitated the superior – inferior movement of the TT in participants with dysarthria to enable the TTto reach peak velocity prior to the jaw. Such articulatory behaviour would adhere to the concept of motor equivalence, it is again and again evident that the motor equivalence playing a central role in disordered speech production of individuals with dysarthria. In the following section, the clinical implications of motor equivalence are discussed.

Implications of studies on motor equivalence

The act of achieving a motor balance as expected for a target sound utterance is explained in terms of **‘motor equivalence’.** The notion of motor equivalence in speech production has also been used to study the motor control strategies that enable coordination between the articulators. Motor equivalence phenomena are of great interest in these regard as they provide insight into how degrees of freedom are selected in various conditions to reach a motor goal. In the present study, rescaling was evident in the amplitude and time trade-offs as seen in the spatial and temporal tracings derived in this study. This seemed to be more evident among dysarthric individuals compared to that of normal individuals indicating a change in strategies selected across the groups to perform the task of speech production.

Data from the present study reflects that it is due to the existence of motor equivalence, dysarthric group is able to exhibit flexibility in general and adaptability under certain circumstances. Since the physical conditions in which a certain motor task has to be fulfilled can vary, different solutions may be possible. These solutions depend on both individual-specific morphology and biomechanical aspects in human speech production, and on the inner and outer conditions that define the effort that must be expended to solve the task. In the present study it is reflected as variation across the individuals in dysarthric group which suggests that motor equivalence gets represented differentially across individuals.

In a nutshell, motor equivalence is very central to the act of speech production and from the present study it is evident that it plays a crucial role in enabling individuals with dysarthria to achieve motor task resulting in acceptable production of target speech. It also contributes to the generation of neural principles that underlie speech motor control, such as the coupling of coordinative structures or the prediction correction-error principle.

Chapter VI

Summary and Conclusions

The present study aimed to compare STI, spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501. This was a preliminary effort in understanding existence of motor equivalence in normal and disordered speech production. The specific objectives of the study were to a) To analyze and compare movement stability and variability of articulatory dynamics in terms of STI for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J), among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501 b) Further, to investigate inter articulatory coordination as measured on spatial coupling and temporal coupling for the articulators of Tongue Tip (TT), Tongue Body (TB) and Jaw (J) among individuals with dysarthria and age and gender matched neuro typical individuals using EMMA AG – 501.

To investigate this, a standard group comparison between normal individuals and dysarthric individuals was considered. Both the groups consisted on 4 participants each, who were matched on age and gender. These participants performed a speech task which required them to produce V-C-V combinations of /aʧa/, /at̪a/ and /aʈa/ along with a carrier phrase “I am saying”. Stimuli were randomized across participants and utterances. They were also instructed to utter the target stimuli ten times as 'clearly as possible’. These responses were recorded kinematically using EMMA AG – 501. The appropriateness of the position data recorded on the EMMA (AG -501) system was visualized using VisArtico software (Version V.0.9.9 - February

2015) and the data was analyzed for STI and spatial – temporal coupling using the MATLAB script of the Speech Movement Analysis, Statistics and Histograms (SMASH) tool (version 0.6) developed by Greene, Wang and Wilson (2013).

The results of the study revealed that STI was higher as expected in the dysarthric group compared to that of normal individuals. Further, there was a lot of variability within the dysarthric group indicating the heterogeneity of the condition itself. Similar findings were reflected on spatial coupling of articulatory points of interest. When both groups were compared for spatial and temporal coordination for speech production, high degree of variability was observed in both the groups. Further, the amplitude peaks in the spatial traces of normal individuals were distinct in terms of representing the up-down movement of the TT, TB and JAW across all the iterations that were analyzed. In comparison to this, the dysarthric individuals showed poor wave morphology in terms of amplitude, which reflects on their inability to target the required range of movement in terms of amplitude for the chain of sounds selected as stimuli in the present study.

An interesting finding from the present study is the nature of motor equivalence in speech production. It enabled rescaling in the amplitude and time trade-offs in the spatial and temporal tracings among the dysarthirc individuals allowing them to achieve motor targets in alternative means. This seemed to be more evident among dysarthric individuals compared to that of normal individuals indicating a change in strategies selected across the groups to perform the task of speech production. It is also noteworthy that motor equivalence gets represented differentially across individuals, as reflected by the variations within the dysarthric group.

Future directions

The present study is an initial attempt towards understanding the nature of motor equivalence in disordered speech production. As it was revealed that motor equivalence strategies vary across individuals future studies should consider a more homogeneous group and if possible a larger study sample.

It would be interesting to see how motor strategies vary across languages. A cross linguistic study that compares across language motor performances may provide better insights into the nature of motor equivalence.

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