VELOCITY PROFILES AND SPATIO - TEMPORAL INDICES (STI) IN THE SPEECH OF CHILDREN WITH CEREBRAL PALSY

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A Dissertation Submitted in Part Fulfilment for the degree of

Master of Science (Speech-Language Pathology),

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ALL INDIA INSTITUTE OF SPEECH AND HEARING

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MYSURU-570006

May, 2016

Certificate

This is to certify that this dissertation entitled **"Velocity Profiles and Spatio – Temporal Indices (STI) in the speech of Children with Cerebral Palsy"** is a bonafide work in part fulfillment for the Degree of Master of Science (Speech-Language Pathology) of the student (Registration No.14SLP033). This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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Declaration

This dissertation entitled **"Velocity Profiles and Spatio - Temporal Indices (STI) in the speech of Children with Cerebral Palsy"** is the result of my own study under the guidance of Dr. R. Manjula, Professor of Speech Pathology, Department of Speech-Language Pathology, All India Institute of Speech and Hearing, Mysuru, and has not been submitted earlier in any other University for the award of any Diploma or Degree.

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INTRODUCTION

Motor speech disorders result from neurologic impairments affecting the planning, programming, control or execution of speech (Duffy, 2013). According to American Academy for Cerebral Palsy and Developmental Medicine (1977), cerebral palsy (CP) refers to non-progressive central nervous system deficit. It is a type of motor speech disorder seen in children due to lesion in a single or multiple locations of the brain, resulting in definite motor and possible sensory abnormalities. It occurs as a result of inutero factors, events at the time of labor and delivery (congenital cerebral palsy) or a variety of factors in the early developing years (acquired cerebral palsy). In addition to motor deficit, other associated disorders may be found. Depending on the type and extent of lesion, the cluster of signs and symptoms seen in children with CP vary leading to subtypes such as Spastic, Ataxic, Flaccid, Athetosis, Mixed and Unclassified (Denhoff & Robinault, 1960). The neuromuscular deficits across the subtypes vary with reference to the tone, physiology of the movement, posture and response to environmental influences (Denhoff & Robinault, 1960). These deficits reflect on all the speech processes starting from respiration to articulation across the subtypes giving rise to specific cluster of characteristics.

Analyses of the speech characteristics of persons with motor speech disorders is carried out using acoustic, behavioral and physiological paradigms. One of the physiological paradigms used is Kinematic analysis, wherein the motion of anatomical parts of interest in space is studied on a temporal scale. Traditionally, kinematic characteristics of speech is studied using instruments such as Electromagnetic Midsagittal Articulography (EMMA), Electropalatography (EPG), Electromyography (EMG), Optotrack etc.

An electromagnetic midsagitalarticulograph (EMMA) is a transduction device that tracks the movement trajectories of a set of articulators of interest (such as lips, jaw and tongue) on which the test sensors are placed, with the reference sensors on nasal bridge & / mastoid region. The data is acquired as an ongoing process of speech production task. The data on EMMA is extracted in two to three dimensions depending on the version of the instrument. For example, in the 3 dimension measures the coordinates x, y and z are utilized to extract movement information in the medial-lateral, superior-inferior and anterior-posterior axes. During recording, the alternating currents which are induced in the sensors by the magnetic fields of the reference coils are separated by their frequencies, digitized and sent in real-time to the control PC. The software stores the current values on the hard drive of the control PC, which helps for the spatial arrangement determination process. Synchronous recording of the speech signal along with the kinematic traces is also possible and this helps in derivation of the position data in time axis.

In this study, EMMA (NDI Wave Speech Research System) was used to extract kinematic data as proposed in the experiment. The NDI Wave Speech Research System is a motion capture system which is specifically designed to track the real-time articulatory oro-facial movements as a non-line-of-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).

Need for the study

Very few studies have been carried out on children with motor speech disorders using kinematic instruments to unravel the different articulatory movements, specifically the lip and jaw movements. Lips and jaw are flexible articulators with varying degrees of freedom and different speech sounds such as bilabials, labiodentals and fricatives require the active participation of these articulators in order to achieve a precise articulation. Often, these articulators are affected in most of the children with speech motor deficits, including CP. Bilabial sounds are reported to be one of the early acquired and mastered sounds in Indian languages. Examples can be drawn from Malayalam (Irfana, 2012; Alphonsa, 2012) and Kannada (Shishira, 2013; Sushma, 2013) languages. The developmental pattern of speech sound acquisition in children with cerebral palsy is also reported to follow similar sequence as in typically developing children, but specific deficits in the articulators relative to the type of neuromotor insult can lead to different articulatory profiles (Irwin, 1955).

Traditionally, articulatory proficiency is studied using perceptual, acoustic and kinematic analysis in typical as well as atypical population. Compared to the perceptual and acoustic analysis, kinematic traces provide a three dimensional view of the articulatory dynamics of different articulators, also facilitating better understanding of the error patterns in three dimensional axes; viz., ***x axis*** (medial – lateral) ***z axis*** (anterior – posterior) and ***y axis*** (superior-inferior). While the acoustic and perceptual analyses provide data after the occurrence of the speech event, the kinematic analysis provides a dynamic view of the ongoing speech event.

Speech motor control in typical children is reported to be continuous till the age of eight years and undergoes refinement from eight to fourteen years of age (Kent, 1976; Goffman & Smith, 1999; Green, Moore, Higashikawa & Steeve, 2000). In comparison to adults, children show slower speech rates and more variable amplitude, velocity, timing and patterning of articulatory movements in the upper lip, lower lip and jaw as evidenced through kinematic analyses (Goffman & Smith, 1999; Green, Moore & Reilly, 2002; Green, Moore, Higashikawa & Steeve, 2000; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean – Muse, 1986; Smith & Zelaznik, 2004; Walsh & Smith, 2002). Adult like stability in movements and speech rates occur with age by fourteen to sixteen years of age (Smith & Zelaznik, 2004; Walsh & Smith, 2002).

The aim of this study is to analyze and compare the kinematic data of lips and jaw for the bilabial sound /pa/ utterances in isolation in children with spastic cerebral palsy and age and gender matched typical children in the age range of 5 to 12 years. The age group of 5 to 12 years is included in this study in order to analyze the speech kinematic characteristics before ***invariance / stability*** is achieved like in adults as reported by many investigators. The point of interest is to understand the difference in ***variability / instability*** seen across typical children and children with cerebral palsy; because the speech motor system is still under the process of maturation in both typical children and children with cerebral palsy, but is overlaid by the issue of impairment in children with cerebral palsy. Only children with Spastic cerebral palsy are included in the study in order to maintain homogeneity and also because of the characteristic presence of hypertonicity and slow voluntary movements seen in this subgroup of children with cerebral palsy which would implicate the production of speech sounds including bilabial sounds. The Velocity Profiles and the Spatiotemporal Index (STI) measures obtained from kinematic analysis will be compared across typical children and children with cerebral palsy to observe for the variability / instability in articulatory dynamics.

Hypothesis

There is no significant difference in the velocity profiles and spatio – temporal indices (STI) of upper lip, lower lip and jaw for the production of iterated /pa/ syllable between the typical and experimental group.

Aim of the study

The aim of the study is to analyze and compare the kinematic traces of lip and jaw movements for the iterated production of bilabial syllable /pa/ in isolation by children with spastic cerebral palsy (experimental group) in the age range of 5 to 12 years and age and gender matched typical children (Typical group), using *Wave Speech Research System* by Northern Digital Inc. (NDI), which is an electromagnetic non line – of – sight motion capture system.

The objectives of the study include analyses and comparison of:

1. Velocity Profiles in the **y axis** (superior-inferior dimension) between the experimental and typical groups.
2. Spatio-Temporal Indices (STIs) of upper lip, lower lip and jaw in the **y axis** (superior-inferior dimension)
3. Velocity Profiles in the **z axis** (anterior – posterior dimension) between the experimental and typical groups.
4. Spatio-Temporal Indices (STIs) of upper lip, lower lip and jaw in the **z axis** (anterior – posterior dimension)

Method

The Wave Speech Research System designed by Northern Digital Inc. (NDI), which is an electromagnetic non line – of – sight motion capture system was used for data collection. Three sensors were placed on the target articulators namely upper lip, lower lip and jaw and one reference sensor was placed on the nasal bridge in a magnetic field of 500 mm cube. The data was derived in the *y,* and *z* axes corresponding to the superior-inferior and anterior-posterior dimensions respectively. A minimum of 12 iterations of the /pa/ syllable produced by the participants was recorded in a noise – free environment. Vis Artico software was used for data visualization and a custom – made script in MATLAB was used for data analysis to derive the time and amplitude normalized velocity profiles and to calculate the STIs in accordance with the objectives of the study.

Implications

Very few studies are reported in the literature, which have used kinematic analyses to address speech motor stability in children with cerebral palsy. The outcome of this study will throw light on the extent of variability in speech motor control in bilabial utterance of children with cerebral palsy when compared to typical children. Since the study includes the age group of 5 to 12-year-old, wherein adult like speech motor stability is not achieved in both typical children (with typical and maturing neuromotor system) as well as children with cerebral palsy (with atypical and disordered neuromotor system), the results will help understand the degree and type of variability in speech motor control between the two groups.

Limitations

1. The instrument, Wave Speech Research System used for the current study deploys self – calibrated sensors, and as per the protocol, no corrections are required to account for the artifacts of head movements in the participants. But this could be treated as one of the intrinsic variable in the study.
2. Inter – rater reliability check for the perception of the iterated /pa/ syllable by the participants could have been carried out.

3. The movement of the upper lip, lower lip and jaw in the anterior-posterior direction as reflected in the z axis would be far less than that of the y axis which depicts the superior-inferior dimensions of movement for /pa/ syllable. In this study however, since the scale selected for the temporal and the spatial dimensions were the same

and because the results of the y and z axis was not represented in the same graph, the differences with respect to the peaks in the amplitude curve for y and z axis has not been reflected diagrammatically.

REVIEW OF LITERATURE

Kinematic analysis is one of the popular methods used to understand the maturity of the speech motor system. Many investigators have addressed the issue of speech motor control in mature adults and also compared with those of acquired conditions such as Parkinson, Amytrophic Lateral Sclerosis etc. In comparison, the literature on developing speech motor system is less and these studies have often addressed the developing nature of speech motor control as a factor of neural maturation.

Smith and Goffman (1998) reported the pattern and stability of speech motor control system in the developmental stages of typical children using kinematic analysis. The study attempted to estimate and compare the spatio - temporal index (STI) in typical 4-year-old, 7-year-old children and young adults. An Optotrak camera tracking system was used in this study with infrared light emitting diode markers in the form of small disks of plastic placed on the lower lip (test sensor) and forehead (reference sensor) of the participants, and the displacement of the lower lip was studied. Thirty iterations of the sentence "Buy Bobby a Puppy" was collected from each of the subject and displacement/velocity data and spatio – temporal index for the same was calculated. The results revealed that the spatiotemporal index for four year olds were significantly higher than 7 year olds and young adults. There was no significant variation in the displacement suggesting that there was a similar type of movement amplitude distribution in all the three groups. The peak velocity of lower lip was higher in adults compared to the two groups of children.

On similar lines, Murdoch, Cheng and Barwood (2013) conducted a study to track the developmental changes of the different articulators from mid – childhood to adulthood, using the Electro Magnetic Mid Sagittal Articulograph (EMMA). The study included 48 participants from different age groups, viz., 6 to 7; 8 to 11; 12 to 17 year olds and adults, with 6 males and 6 females in each age group. All the subjects were native English speakers and were screened for articulation at the single word and sentence level using the Weiss Comprehensive Articulation Test (Weiss, 1980) in case of children and on single word section of the Multiple Word Intelligibility Test (Kent et al., 1989) and the sentence section of the Assessment of Intelligibility of Dysarthric Speech (Yorkston and Beukelman, 1981) for adults. The Articulograph AG – 200 system was used in the midsagittal view to study the tongue and lip movements (test sensors), with reference sensors placed on nasal bridge and the maxilla. The audio recording was carried out in synchronization with the kinematic data. Five CV and CVC combinations with the target sounds /t/, /s/, /l/, /k/ and /p/ which were embedded in short sentences were used as the stimuli and the subjects were instructed to iterate each of the token at least five times. The displacement, velocity and temporal measures were derived. The results revealed that there was a decrease in the movement duration with an increase in the age. No significant changes across the selected age groups were observed for the displacement and velocity profiles, except for few significant changes for the lingual and labial stops and the consonants /s/ and /l/. It was concluded that the movement duration was more sensitive in understanding the stability and maturity of the speech motor control system.

Very few studies have been conducted on children with disordered speech output owing to factors such as limited speech output, presence of comorbid / associated conditions, postural instability etc which restrict the use of kinematic approaches in understanding the speech motor stability in such individuals. Lofqvist and Gracco (1997) used a time series design to study the lip and jaw kinematics along with the measures of air pressure and force before, during and after the closure of the oral structures for the production of bilabial stop consonants in normal adults. The Kinematic measures were obtained using a three – transmitter magnetometer system, by placing the experimental sensors on the upper lip, lower lip, and lower incisors and the reference sensors on the nasal bridge and upper incisors. Five typical English speaking adults (three female and two males) were included as participants in this study. To measure the oral pressure, a miniature pressure transducer was used. A set of VCV sequences, where the pressure consonants /p/ or /b/ occurred with the first vowel /a/ and the second vowel being one of the vowels from among /a/, /i/ and /u/ was chosen. The participants were instructed to produce the VCV sequences at least 12 times. Results revealed differences in the peak force and peak velocity of the upper and lower lips. The peak force of the upper lip was lesser and slower in the onset compared to the lower lip. Concomitantly, the peak velocity of the upper and lower lip also varied; the lower lip reached the peak prior to the oral release whereas the upper lip reached the peak after the oral release. No significant difference and consistency was observed for voiced consonant and on second vowel with respect to the displacement pattern and peak velocity.

Investigators have addressed the effect of speech rate on the parameters of amplitude and movement velocity as a reflection of speech motor control. There were however, inconsistencies in the results as there were considerable variations in the experimental design used by various investigators to derive the measures of interest. Adams and Kent (1993) attempted to study the effects of varying rate of speaking on the movement velocity profiles, by controlling the following factors in the experiment: (a) a wide range of speaking rates were used in comparison to a maximum of two speaking rates used in the previous studies. (b) An autophonic scaling procedure designed by Lane and Grosjen (1973) was employed in the study to help the participants manipulate their speaking rates over a wide range. In comparison, the previous studies used self – selection method for changing the speaking rates which was critically commented as a less effective procedure by Ostrey et al. (1987). (c) The effect of speaking rates on the lower lip and tongue tip sounds were addressed in this study as these sounds occurred most frequently compared to other sounds. (d) The velocity curves were quantified with additional parameters such as time required to reach the maximum peak, the skewness and kurtosis of the velocity profile and the number of peaks for single movement. Adams and Kent (1993) recruited five native speakers of English aged between 19 to 35 years as participants. They were instructed to repeat the phrase "Tap a Tad" (which included stop consonants with palatal and bilabial place of articulation) as normally as possible at a constant loudness (monitored using a VU meter) at five different speaking rates. The habitual speaking rate was considered as the base and participants were instructed to increase or decrease the speaking rates as per the prescribed block of "40, 20, 10, 5 and 2.5". Each speaking rate was iterated at least 10 times within each block which was randomized across the participants. Practice trials were provided prior to the experiment. An X – ray microbeam system was used to measure the movements of the lower lip and the tongue tip during various speaking tasks in mid sagittal view, tracked along the x axis (anterior – posterior dimension) and y axis (inferior – superior dimension). The results revealed significant increase in movement duration with decreasing speaking rates and a wider range of movement for the tongue tip compared to the lower lip. A single, large and symmetrical peak in the velocity profiles was observed for the faster speaking rate condition.

Few other studies addressed the effect of linguistic, motor and cognitive demands on the speech motor control. . The assumptions of these studies were that the occurrence of speech is governed by the linguistic, cognitive and motor demands in a given situation. Dromey and Bates (2005) attempted to study speech motor control in participants performing two tasks simultaneously, with the interest to understand the effect of degree of interference on speech motor control as this depends on the degree of similarity between the two tasks. They tested the hypotheses that change in the displacement and velocity of the articulatory movements depends on the interference caused by motoric, linguistic and cognitive demands. Twenty college students who were native English speakers (10 males and 10 females) were included. A head – mounted strain gauge system was used in the experiment. Participants were given seven tasks, of which four were isolation tasks and three were combination tasks. The isolation tasks consisted of speech, linguistic, cognitive, and visuomotor tasks presented to participants in a random order. The target articulators studied included lips and jaw. In the speech only condition, participants repeated a phrase with bilabial consonants 15 times. In the linguistic only condition, the participants were asked to generate a meaningful and grammatical sentence from jumbled words. In the cognitive only task, the participants were instructed to solve a 2 digit math subtraction. In the visuomotor only task, the participants were instructed to click on the randomly appearing objects on a computer monitor using a mouse. In the simultaneous tasks of speech and linguistics, the participants were instructed to repeat the target sentence and add the constructed sentence formed out of jumbled words as part of the speech and linguistic task. For the combined task of speech and cognition, the participants were asked to solve the problems and repeat the target sentence. For the combined task of speech plus visuo motor condition, the participants were instructed to repeat the target sentence along with clicking on the randomly appearing objects on the computer screen. Peak velocity and synchrony of lip and jaw movement displacement was computed. From the time and amplitude normalized data, spatio – temporal index for the lip and jaw was computed. The results revealed a significant decrease in the displacement for the lip and jaw in combined task conditions, and a significant increase in utterance duration in the speech combined with cognition condition.

Also, a significant increase in spatiotemporal index was observed in the simultaneous tasks compared to the isolation tasks.

Kinematic analysis has been used by few investigators to understand the underlying speech motor dynamics in children with motor speech disorders. Nijland, Maassen, Hulstijn and Peters (2004) conducted a study to test the hypothesis that the development of speech motor control is dependent on the acquisition of coordinating gestures which is deficient in persons with developmental apraxia of speech. In order to test this hypothesis, native Dutch speaking children aged 4;3, 9;0, and 11;10 years with the diagnosis of developmental apraxia of speech (experimental group) with matched group of controls were tested. The children were instructed to repeat monosyllables which increased in complexity (CV, VC, C1C2V and C2VC1) and these were recorded on AG 100 electromagnetic articulograph in the mid sagittal plane. The test sensors were placed on the tongue tip, tongue body, upper lip and the lower lip. The relative phase in the kinematic plots of each of the articulator points revealed a significant difference in the groups with greater deviation in the experimental group.

Kinematic analysis was conducted by Gooze´e, Murdoch, Ozanne, Cheng, Hill and Gibbon (2007) on children with articulation or phonological disorder, to study the speech motor control and tongue kinematics. Three children (one female and two males) ranging from 9.58 to 11 years diagnosed as having persistent articulation/ phonological disorder were included as participants along with age and gender matched children. Single syllables /t/, /s/ and /k/ were uttered by the participants and they were measured using electropalatography. Before the experiment, the children were tested on Verbal Motor Production Assessment for Children (Hayden & Square, 1999), Fisher–Logemann Test of Articulation Competence (Fisher & Logemann, 1971), Children's Speech Intelligibility

Measure (Wilcox & Morris, 1999), and Assessment of Intelligibility of Dysarthric Speech (Yorkston & Beukelman, 1981), which showed that the three children showed evident disruption in speech motor control reflecting a dysarthric component (in all three children) and dyspraxic component (in two children) . The strength and endurance measures of the anterior tongue were measured at 10% and 20% levels of pressure. The electromagnetic articulography AG – 200 system was used to measure the movements of tongue tip and tongue body. The children were instructed to repeat 80 words that included the targeted lingual consonants with different place of articulation. Various parameters such as maximum velocity, acceleration, deceleration, distance and duration were calculated and analyzed to understand the coordination between the tongue tip and tongue body movements. The results revealed that the measures were highly variable in these children and deviant compared to the control group, implying a poor and immature speech motor control in children in the experimental group. Few other studies have also included persons with dyasrthria for kinematic analysis. Forrest, Weismer and Turner (1989) examined the acoustic, kinematic and perceptual correlates of speech in persons with Parkinson disorder. The target articulators considered for kinematic analysis were the upper lip, lower lip and jaw. Nine male participants with the diagnosis of Parkinson's in the age range of 58 to 76 years and eight age and gender matched normal subjects without any neurological problems were considered. The participants were asked to produce target sentences containing bilabials; with each sentence repeated 25 times. The sentences were randomized across and within the participants. The strain gauge mounted on cantilever beam was used to derive the kinematic measures for inferior – superior movements of the target articulators. The kinematic measures for the different opening and closing movements of the articulators were extracted. There were no significant differences in the duration of the opening gesture for the target articulators between the groups. Comparison of peak velocities across the two groups revealed poorer peak velocities with low amplitude in the experimental group. The closing gesture for the lower lip was more affected in the experimental group compared to the control group. It was also observed that as the velocity of the movements increased, the duration of the gestures also decreased. The amplitude and velocity of jaw movements was not dependent on the severity of dysarthria; whereas, the amplitude and velocity of lower lip varied with the severity of dysarthria. The velocity was lower in persons with severe dysarthria when compared to persons with moderate and mild dysarthria.

Wong, Murdoch and Whelan (2010) compared the lingual kinematics using Electromagnetic articulography - AG – 200 system in 8 individuals with Parkinson's disease in the age range of 56 to 78 years and the control group. The reference sensors were placed on the bridge of the nose and maxilla and test sensors were placed on the tongue tip, tongue back and the jaw. A sentence repetition task with 5 iterations of each sentence was considered. The sentences included alveolar consonants to test the movements of the tongue – tip; and velar consonants to test the movements of the tongue body. The data was extracted and analyzed for displacement, velocity and acceleration/ deceleration profiles. The experimental group showed an increase in all the three profiles in the release phase for both the alveolar and velar sentences. In the approach phase for the velar consonant production, the experimental group showed an increase in the tongue movement velocity, but there was no significant difference in the acceleration/ deceleration profiles for the same. Similarly, no significant differences were observed between the two groups for alveolar consonant production. The duration was longer in the experimental group. Overall, the results revealed that the persons in the experimental group had a reduced range of the lingual movements.

Yunusova, Green, Lindstrom, Ball, Pattee and Zinman (2010) attempted to identify early predictors for the decline of intelligibility of speech using kinematic measures using a longitudinal design. The study aimed to assess the parameters of individual's speech movements, measures of rate of speech and speech intelligibility and study its potential as early predictors. The study tested the hypothesis that the kinematics of the articulator's changes with the progression of the disease and these changes could be the early predictors of the onset of disease in the bulbar system. Three males with bulbar amyotrophic lateral sclerosis with no significant history of any communication disorders were included in the study. The participants were instructed to repeat a sentence five times where in the target words were "bat, fast, feasts, cake, and wait". A 3D motion infrared video camera system was used to obtain the kinematic data. The upper lip, lower lip and jaw movements were tracked using the same. Prior to the kinematic assessment, the individual's speech intelligibility and speaking rate was calculated. The Sentence Intelligibility Test (Beukelman, Yorkston, Hakel, & Dorsey, 2007) was used to calculate each participant's intelligibility and the speaking rate was calculated as the number of words that were produced by the participant per minute. The path, distance, range of motion, average speed and duration of the opening – closing gestures of the lip were calculated and analyzed. The results revealed that two speakers out of the three showed significant changes in the average speed and path duration by three months as factors that could affect the speech intelligibility. As the disease progressed in all the participants, the movement duration of the articulators were longer and correlated with a decline in the intelligibility. The study concluded that movement measures can serve as early predictors of the disease progression.

Rong, Loucks, Kim, and Johnson (2012) studied the articulatory movements in children with spastic cerebral palsy by analyzing the relationships between F2 slope, movement of the tongue and the overall intelligibility of the alveolar stops and fricatives.

The study focused on the different kinds of testing procedures – articulatory, acoustic and perceptual assessment, and tested the hypothesis that the reduction in the overall intelligibility of speech in such individuals correlated with the decrease in the slope of F2 for the diphthong /aI/. It also hypothesized that the labored and decreased tongue motion correlated with the decrease in the slope and intelligibility and deviant patterns of the submental muscles. Three individuals with spastic cerebral palsy between 22 to 43 years were considered for the study. Three age matched speakers who were screened for any neurological disorders were considered as the control group. Orthographic transcription and perceptual ratings were carried out to estimate the individual's intelligibility of speech. The target consonants selected were alveolar consonants with CV or CVC combinations, with V kept constant as diphthong /aI/. The 3D electromagnetic articulography - AG500 was used. The test sensors were placed on the upper lip, lower lip, chin and the upper muscles of the neck to check for the muscle activity responsible for making the various mouth gestures. The stimulus was presented to the subjects on the computer monitor using PowerPoint and the subjects were instructed to read the same and repeat the stimulus three times. The data was analyzed for duration, displacement, maximum velocity and acceleration/ deceleration for tongue and jaw. The z axis was considered for measurements which provided information regarding the inferior – superior dimension. The results revealed that the duration of the release phase for both the tongue and jaw movements was longer in individuals with cerebral palsy in comparison to the control group. The amplitude was reduced in individuals with cerebral palsy for the tongue – tip movements. In contrast, the amplitudes were higher in these subjects for jaw movements. A high variability between the individuals with cerebral palsy and among the control and experimental group was observed. On comparing the activation levels of the submental muscle activity using normalized peak amplitude, it was observed that the individuals with cerebral palsy had a very low rate of activation as opposed to the control group. The overall kinematics in individuals with cerebral palsy was prolonged with reduced displacements. A negative correlation was observed between the F2 slope and the tongue tip kinematics, whereas a positive correlation was observed between the F2 slope and jaw kinematics. A wide range of associations were observed in the correlations between the overall intelligibility of speech and slope of the F2 trajectory. The investigators concluded that the more severe the deviations in tongue kinematics, the more severe was the speech intelligibility score in individuals with cerebral palsy.

Most of the studies addressing the speech motor control in individuals with cerebral palsy have used the instruments such as EMMA (AG 200 & AG 500), Optotrack etc to derive the kinematic measures of interest. This study aims to measure and compare the kinematic traces of lips and jaw in children with cerebral palsy using *Wave Speech Research System* by Northern Digital Inc. (NDI), which is an electromagnetic non line – of – sight motion capture system, designed specifically for speech research. The system calculates and records, in real time, the position of discrete points on, for example, the tongue, palate, jaw, lips and face. To the best of the knowledge of the investigator, there is no reported literature using this instrument to measure the kinematic traces of children with cerebral palsy.

METHOD

This study proposed to analyze and compare the kinematic traces of lip and jaw movements for the production of bilabial syllable /pa/ in isolation by typical children (Typical group) and children with spastic cerebral palsy (Experimental group) in the age range of 5 to 12 years, using *Wave Speech Research System* by Northern Digital Inc. (NDI), which is an electromagnetic non line – of – sight motion capture system.

Hypothesis

There is no significant difference in the velocity profiles and spatio – temporal indices (STI) of upper lip, lower lip and jaw for the production of iterated /pa/ syllable between the typical and experimental group.

Aim of the study

The aim of the study is to analyze and compare the kinematic traces of lip and jaw movements for the iterated production of bilabial syllable /pa/ in isolation by children with spastic cerebral palsy (experimental group) in the age range of 5 to 12 years and age and gender matched typical children (Typical group), using *Wave Speech Research System* by Northern Digital Inc. (NDI).

The objectives of the study include analyses and comparison of:

1. Velocity Profiles of upper lip (UL), Lower lip (LL) and Jaw (J) in the **y axis** (superior-inferior dimension) between the experimental and typical groups.
2. Spatio-Temporal Indices (STIs) of UL, LL and J in the **y axis** (superior-inferior dimension)
3. Velocity Profiles of UL, LL and J in the **z axis** (anterior – posterior dimension) between the experimental and typical groups.

4. Spatio-Temporal Indices (STIs) of UL, LL and J in the **z axis** (anterior – posterior dimension)

Study design

A standard group comparison study design was employed in this study. The two groups included the experimental group of children with spastic cerebral palsy and the typical group of children matched for age and gender of the experimental group.

Participants

A total of 10 participants ranging from 5 to 12 years of chronological age were included in the study. They were divided into two groups:

Experimental group: with 5 children diagnosed as spastic cerebral palsy in the chronological age range of 5 to 12 years. The demographic details of the participants are given in Table 1.

Typical group: with 5 children matched for age and gender of the children in the experimental group.

Inclusion criteria for the selection of the experimental group were as follows:

1. Children diagnosed as spastic cerebral palsy by a neurologist were included in the study.
2. Those with associated problems such as presence of sensory impairments (hearing, vision and tactile) and cognitive limitations were not included (based on a WHO screening checklist administered by the investigator (WHO Work group version, 2004).
3. The language age of the children was equal to or less by 6 months compared to the chronological age in the receptive and expressive domains as evaluated using the verbal language test (Swapna, Prema & Geetha, 2010).

4. The children could articulate the syllable /pa/ in isolation clearly and intelligibly, as tested and perceived by the investigator.

Inclusion criteria for the typical group:

Children matched for age and gender of the participants in the experimental group without any history of hearing, vision, intellectual, and neurological, and language disorders were considered for the study.

Table 1

The demographic details of the participants included in the experimental group

Participants	Age (in years) & Gender	Socio-Economic status	Neurological diagnosis	Topography
P-1	6 / M	Middle	Spastic CP	Hemiplegia (R)
P-2	7 / F	Middle	Spastic CP	Hemiplegia (R)
P-3	6 / M	Middle	HIE Sequale-Spastic CP	Quadriplegic
P-4	11 / F	Middle	Spastic CP	Quadriplegic
P-5	10 / F	Middle	Spastic CP	Paraplegia

Equipment

1. The *Wave Speech Research System* by Northern Digital Inc. (NDI) was used to collect the data. The *Wave system* is an electromagnetic non line – of – sight motion capture system, designed specifically for speech research. The system calculates and records, in real time, the position of discrete points on, for example, the tongue, palate, jaw, lips and face. As an option, audio is simultaneously recorded and synchronized with the motion capture data for post – hoc analysis. The Wave Speech Research System by Northern Digital Inc. (NDI) that was used for collection of data included the following main components and accessories: Field generator, System Control Unit (SCU), 4 Sensor Interface Unit (SIU), 4 Wave connector block cable

assembly, Disposable sensors (4 channels of 8 chosen), Synchronization cables and Field Generator Mounting Arm. The instrument works on the principle of electromagnetic articulography (EMMA) system which supports three dimensional (3D) tracking of articulatory movements at 5 or 6 degrees-of-freedom (5-DOF, 6-DOF). Sensors are placed on the articulatory structure of interest in an electromagnetic field volume (300 mm cube or 500 mm cube) that is projected outwards from the Field Generator's face, offset by 40 mm from the Field Generator. Sensors placed in 5-DOF allow tracking of x, y, and z spatial coordinates, as well as angular coordinates characterizing rotation about the transverse axis (pitch) and anterior–posterior axis (roll). 6-DOF sensors have the added capacity for tracking angular coordinates characterizing rotation about the inferior–superior axis (yaw). The standard NDI Wave system has eight input channels and records sensor movements with a 100-Hz sampling rate. The *x*, *y*, and *z* axes corresponds to the medial-lateral, inferior-superior, and posterior-anterior directions, respectively (Berry, 2011).

The configuration selected for data collection in this study included 4 channels (4 sensors) in 5 DOF in 500 mm cube field. Of the 4 sensors, one sensor served as the reference sensor which was placed on the nasal bridge and 3 sensors served as test sensors, which were placed on the upper lip, lower lip and jaw respectively. All the kinematic data of the test sensors was derived with respect to the reference sensor. Figure 1 provides an over view of the *Wave Speech Research System* by Northern Digital Inc. (NDI). Figure 2 provides a view of participant tested on the *Wave Speech Research System* by Northern Digital Inc. (NDI). Figure 3 provides a view of the screenshot of the kinematic data on the *Wave Speech Research System* by Northern Digital Inc. (NDI)

Figure 1: *View of the Wave Speech Research System by Northern Digital Inc. (NDI).*

Figure 2: *Sample of participant with placement of sensors*

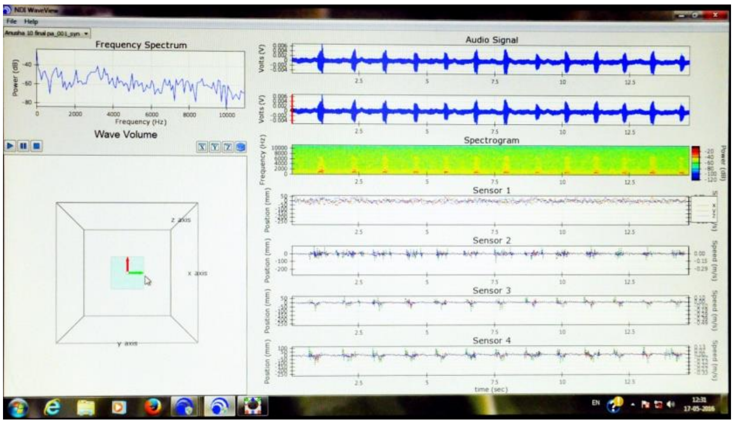


Figure 3: *Screenshot of the kinematic data derived on Wave Speech Research System*

2. *VisArtico software*, (Version V.0.9.9 - February 2015) is an articulatory data visualization tool in which the graphical user interface is the most important component. The user interface is composed of three main view panels: the 3D spatial

view, the midsagittal view, and the temporal view. The position and orientation of each sensor in the articulograph's reference space is displayed in the 3D view panel. The midsagittal view panel presents, in a 2D plane, a midsagittal slice of the vocal tract that can reveal the contour of the tongue, lips, and jaw. This helps in better understanding of the data derived from the speech wave recording. The temporal view panel displays a time signal representation of individual coil trajectories, synchronized with the acoustic recording. In VisArtico, there is facility to simultaneously animate the three different views of the data in a synchronized way (Ouni, Mangeonjean & Steiner, 2012). The recorded data from Wave Speech Research System was transported to VisArtico for visualization and inspection of the plots and verification of the position data before derivation of values of velocity profiles. Figure 4 provides a screen shot view of the data on VisArtico.

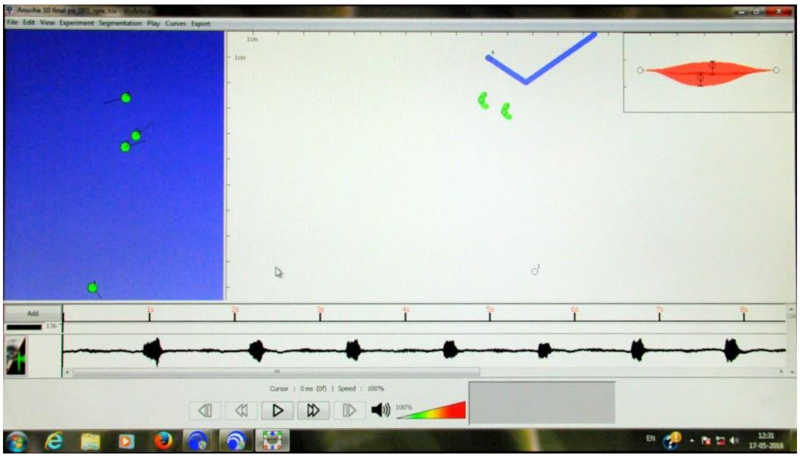


Figure 4: Screen view of the data on VisArtico.

2. *MATLAB* (The Mathworks of Natick, Massachusetts, USA) was used for data analysis and derivation of velocity profiles and STI measures in both groups.
3. *Speech Movement Analysis, Statistics and Histograms* (SMASH) tool (version 0.6) developed by Greene, Wang and Wilson (2013)

The VisArtico, MATLAB & SMASH were installed in a Windows 8 based laptop and data analysis was carried out on the same.

Set up: The data recording was carried out in a quiet laboratory setting and data from each child was collected individually. A noise free environment with adequate lighting and ventilation and minimal distractions in the environment was ensured.

Stimuli: Bilabial speech sound /pa/ was elicited in isolation and each participant was instructed to repeat the syllable a minimum of 12 times.

Ethical consideration: Written informed consent was obtained from parent of each participant included in the study. The parent and the child were counseled and informed that the entire procedure is noninvasive.

Presentation of the Stimuli and instruction to the participants

The participant was seated comfortably within the magnetic field of the Wave Speech System. The participant was initially provided practice for correct articulation of /pa/ before data recording. After ensuring that the participants can utter the stimuli in the correct manner, producing the /pa syllable which was perceived auditory as being correct, they were instructed to look at the computer monitor placed in front of them on which a visual prime was displayed at the habitual rate of the participant (the habitual rate of each participant was tested before the commencement of the experiment) and the participant was instructed to utter the stimuli 'as clearly as possible' after every visual prime display. They were instructed to repeat the syllable /pa/ a minimum of 12 times. Practice was provided until the child had followed the instruction.

Procedure for data acquisition

Calibration: As the sensors are self-calibrated, no additional calibration was required for the Speech Wave instrument as specified by the standards of the equipment.

Data Acquisition: Once the participant was seated comfortably within the generated magnetic field, and had understood the instructions for producing the stimuli sets, the reference and test sensors were fixed on the child for data acquisition. The reference sensor was placed on the nasal bridge and three test sensors were placed on the mid border of upper lip, lower lip and mid position of lower jaw (below and in line with the sensor in the lower lip) and these were secured in place of interest using a bio adhesive tape. The child was instructed to repeat the stimuli a minimum of 12 times after the visual prime (which was appearing according to the habitual rate of the speech of the child in front of them). Data was acquired in both top (superior-inferior) and side view (anterior-posterior) (*y*, and *z* axes respectively). Data of each child was recorded and stored in the device as designated files.

Reliability check

Inter rater reliability check for data acquisition: The data acquisition procedure was repeated for two participants (one each from the typical and experimental group) by two judges (Speech – language pathologists) who were trained in this procedure to check for reliability of data acquisition. Point by point agreement of the derived data by the investigator and the two judges was carried out to check for reliability and the same was converted into percentage. The level of agreement between the investigator and two judges were as follows:

Investigator and judge 1: 80 %

Investigator and judge 2: 90 %

Judge 1 and judge 2: 84 %.

Intra rater reliability check for data acquisition: This was carried out only for the investigator. The investigator repeated the procedure of data acquisition of one participant each in the typical and experimental group for the 2nd time, after a gap of 15 days. Point by point agreement of the derived data by the investigator in the 1st and 2nd instance was compared and converted into percentage. The intra rater reliability was found to be 94% for the child from typical group and 85 % for the child from experimental group.

Measures extracted and analysis:

The following steps were followed to derive the velocity profiles and STI indices in y and z axes as per the stated objectives of the study:

a) The acquired data from the *Wave Speech Research System* by NDI was exported on to the VisArtico software (Version V.0.9.9 - February 2015) in order to visualize and verify the positional data for the iterations of the bilabial /pa/. VisArtico imports and reads the *tsv* files and the sound files (wav format) from the NDI Wave system and portrays the data in a 3D view, mid-sagittal view and temporal view to facilitate better visualization of the data. An additional acoustic view also can be displayed for better understanding of the obtained position data.
b) The data along with the audio file of each of the participant was then exported on to the Wave View module of the NDI Wave Speech Research System. The Wave View module provides a display of the frequency spectrum, spectrogram, 3D view of the wave volume and kinematic data specific to each sensor in terms of position and velocity. The position and velocity data for each sensor of each of the participant across the two groups were extracted using the same.
c) The audio signal was then imported to PRAAT software (Version 5.0.35), where in the time frame was set to exclude the first and the last three iterations of a total of

twelve, in order to avoid the initial and terminal lags and to account for stable speech motor behavior.

d) The kinematic data obtained from the NDI Wave View module was exported to Microsoft Excel and the data in the time frame as obtained from PRAAT analysis was saved for further analysis.

e) The time frame for each iteration of /pa/ was extracted individually and the position data for each iteration was saved in the Microsoft Excel format per iteration in the chain of iterations and for all the iterations per participant.

f) The data saved in Microsoft Excel was converted to *csv* format (comma delimited) in order to make it compatible for further analysis using the MATLAB programme.

g) *Speech Movement Analysis, Statistics and Histograms (SMASH)* tool (version 0.6) developed by Greene, Wang and Wilson (2013) was used for articulatory data analysis and processing. This is an in – built customized program which is compatible with MATLAB to yield the required output based on data processing. It is Graphical User Interface supported program, which aids in processing and analysing articulatory data extracted from both EMMA (Cartsens) and NDI electromagnetic Articulographs (as applicatble in this study). Prior to the use of this program in MATLAB, the program was customised for the individual system on which the analyses were performed. A customised template was created defining the coordinates of the system, number of sensors used for testing, the sampling frequency, sensor channel labels and the signal types. The program allows a spatial and a time – series analysis of the input. As per the objectives of the study, *velocity profiles* for the three articulators, namely the upper lip, lower lip and the jaw in y – axis (superior – inferior dimension) and z – axis (anterior – posterior dimension) was analyzed. Further, the spatio – temporal indices (STIs) were also estimated for the two axes across all the articulators. *Velocity profiles* were defined as the continuous, dynamic parameters of naturally occurring movements over time. *STI* was defined as the degree to which a set of movement trajectories converge after linear normalization with respect ot time and amplitude. Time and Amplitude normalization of the obtained waves was first carried out. Standard deviation was computed at 2% intervals across the iterated utterances at one point in relative time. An average of 50 standard deviations was obtained and this value was referred to as STI. The SMASH program automates this procedure during data analyses after setting the appropriate parameters. The entire program uses a menu – driven approach and hence by selecting the appropriate commands, the velocity and the STI for each of the articulatory positions, viz., upper lip, lower lip and jaw per participant was computed. The group data was later derived in a similar fashion, represented in color and compared.

The results are reported in the next chapter

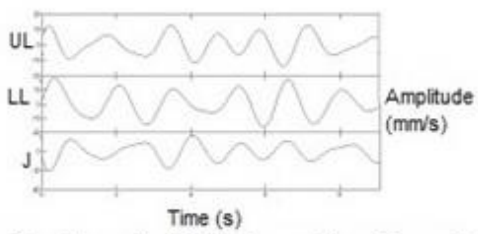
RESULTS

The study proposed to analyze and compare the kinematic traces [using *Wave Speech Research System* designed by Northern Digital Inc. (NDI)] of typical children (Typical group) and children with spastic cerebral palsy (Experimental group) in the age range of 4 to 12 years for the lip and jaw movements during the production of /pa/ syllable in isolation. The specific objectives included comparison of the velocity profiles and spatio – temporal indices (STI) of the upper lip, lower lip and jaw for iterated /pa/ production across the two groups in the two axes: y axis (superior - inferior –dimension) and z axis (anterior - posterior –dimension). The results are presented under the following heads:

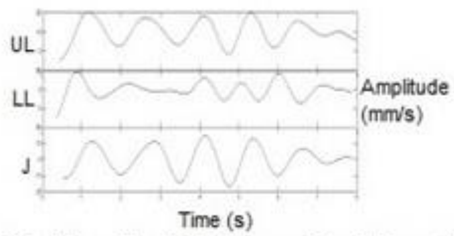
A. Comparison of velocity profiles across groups in the y – axis (superior - inferior dimension)
B. Comparison of spatio temporal indices across groups in the y – axis (superior - inferior dimension)
C. Comparison of velocity profiles across groups in the z – axis (anterior – posterior dimension)
D. Comparison of spatio temporal indices across groups in the z – axis (anterior – posterior dimension)

A. Comparison of velocity profiles across groups in the y – axis (superior - inferior dimension)

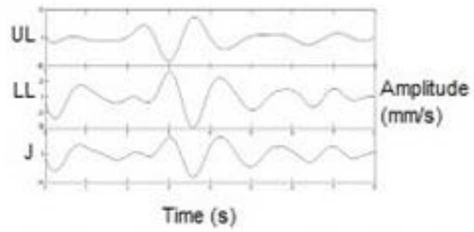
The time and amplitude normalized velocity profiles of the experimental and typical group derived from the y axis are presented in Figures 5 (a & b) to Figures 9 (a & b).



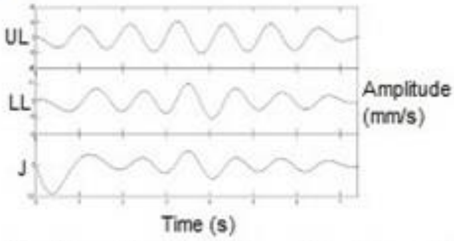
Figures 5 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 1 in Experimental group



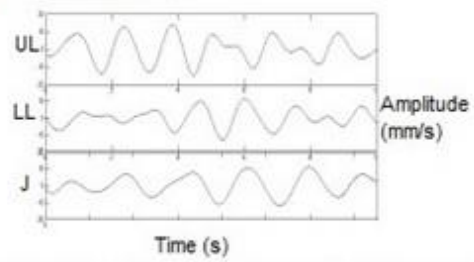
Figures 5 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 1 in Typical group



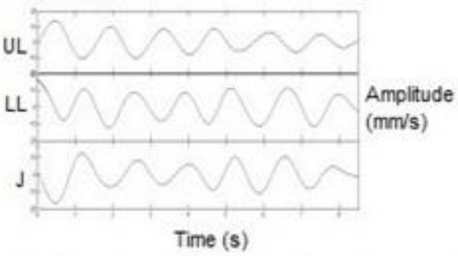
Figures 6 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 2 in Experimental group



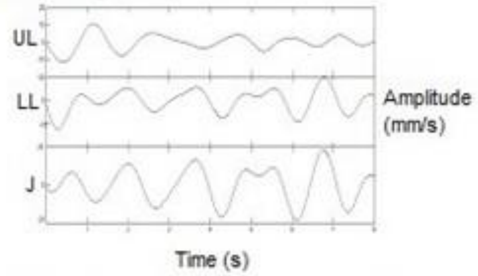
Figures 6 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 2 in Typical group



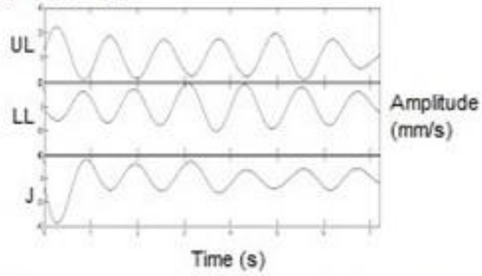
Figures 7 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 3 in Experimental group



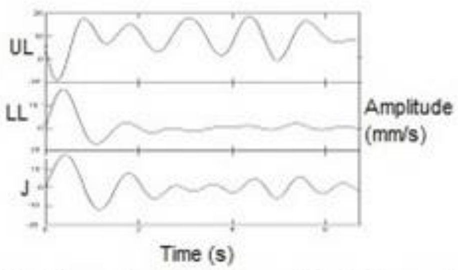
Figures 7 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 3 in Typical group



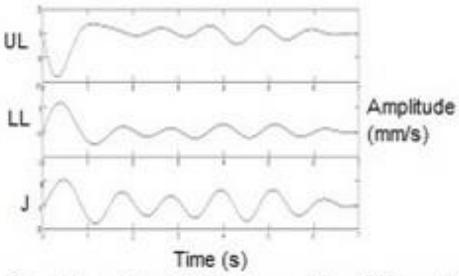
Figures 8 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 4 in Experimental group



Figures 8 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 4 inTypical group



Figures 9 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 5 in Experimental group



Figures 9 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Y axis for Participant 5 in Typical group

Comparison of Figures 5 a and b reveals that the time taken by the typical participant to produce the six iterations of /pa/ was comparatively lesser (8 seconds) than the experimental participant (9 seconds). The wave morphology of the upper lip and jaw in the typical participant is robust and clear for the iterations, which is also true in the experimental participant 1 for all the 3 articulators. Except for the difference in one instance of iteration for the lower lip in the typical participant, the wave morphology for the cognate articulators show clear coordination and phase differentiation across upper lip (UL), lower lip (LL) and jaw movements. In comparison to the typical participant, in the experimental participant, at least five of the six iterations reflect good wave morphology across the articulators but show poor phasic movements between the articulators. For example, the upper lip is out of phase with the lower lip; although the lower lip and jaw movements were in phase with each other.

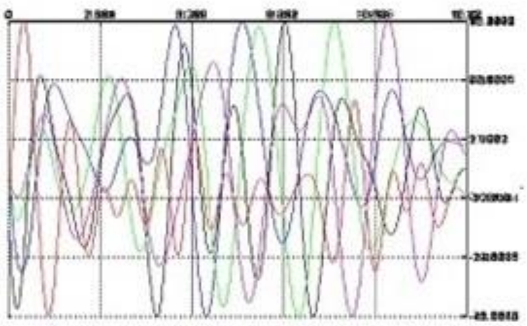
From Figure 6 a and b, it is seen that the time taken for iterations of /pa/ by the experimental participant 2 was longer (8 seconds) compared to that of typical participant 2 (7.5 seconds). When compared to the typical participant, in the experimental participant 2, although the amplitudes of the velocity profiles are comparable, there is poor wave morphology across the three articulators (at least in three out of 6 iterations), reflecting non distinct articulation of the /pa/ syllable, specifically with respect to the amplitude of the peaks in the experiment participant 2. Interestingly, however, the phasic movements are preserved with good coordination in the movements between the three articulators.

Comparison of the velocity profiles of the 3rd pair of participants (Figures 7 a and b) reveals that the time taken by the experimental participant for the iterations of /pa/ syllable is prolonged (11 seconds) compared to that of the typical participant (8 seconds). The amplitude of the waves for the iterations is less distinct and compromised in the experimental participant compared to the typical participant. The coordination and phasic integrity between the lower lip and the jaw movements is well preserved; but the same is not true with respect to the upper lip in the experimental participant. Also, multiple peaks in the upper and lower lip profiles of the experimental participant reflects poor neuromotor control in these structures although the participant did produce good, acoustically acceptable and perceivable /pa/ syllables.

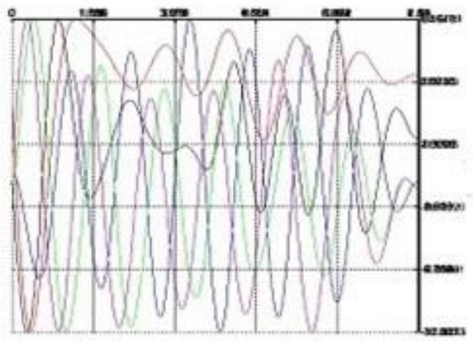
The Figures 8 a and b reveal that as in the experimental participants 1 to 3, the duration for the iteration of /pa/ syllables in the experimental subject was longer (8 seconds) compared to the typical participant (7 seconds). In the typical participant, good wave morphology and coordination for the cognate articulators were evident. In contrast, in the experimental participant, it was observed that the morphology was good only for the upper lip compared to the lower lip and jaw. In addition, although the lower lip and jaw movements showed relatively better phasic integrity, it was not the same when upper lip is compared with that of lower lip and jaw. The interesting point observed in the experimental participant was that the peaks in the wave morphology were distinct in the jaw but not so in the lower lip, suggesting that an intelligible production of /pa/ in the participant was probably due to the movements of the upper lip performed against a more or less indistinct movement of the lower lip aided mostly by exaggerated jaw movements.

Comparison of the velocity profiles in Figure 9 a and b reveals that the amplitude of movements in the upper and lower lip in the typical participant was less compared to that of the jaw, although there were distinct peaks reflecting the iterations in this participant. Unlike the other four experimental participants, this participant revealed lesser duration (6.5 seconds) for the 6 iterations compared to that of the typical participant (7 seconds). The results of the 5th experimental participant were very similar to that of the 4th experimental participant wherein, the movement amplitude of the upper lip was less compared to that of jaw. The upper lip however, showed good morphology like that of the jaw but there was poor coordination between the three structures and also poor phasic match between the three articulators.

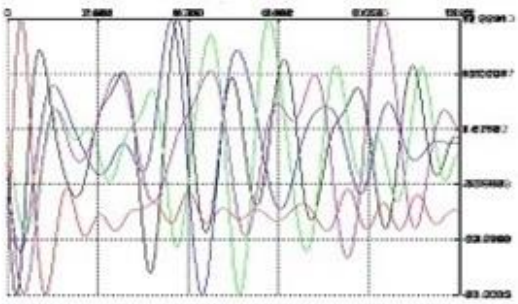
Overall, the results point to increased duration in the experimental participants (except for the fifth pair) with duration being more than that of the typical participants. In terms of wave morphology, majority of the typical children showed good wave morphology with preserved peaks representative of the iterated productions of /pa/ syllable (except for the lower lip in typical participant 1 and upper lip in the typical participant 5). In the experimental group, except in the participant 2, the velocity profiles of the UL, LL 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 experimental participants 4 and 5, wherein the upper lip and lower lip did not show good peaks but the jaw movements were relatively preserved to represent the iterated movements. The points observed herewith are supported in the representation of group data for all the 5 participants of both the groups on a single plot [Figures 10 (a & b) to 12 (a & b)].



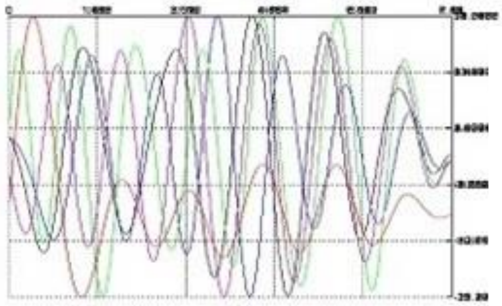
Figures10a: Normalized Velocity profile of Upper lip (UL) in Y axis for five participants in the Experimental group



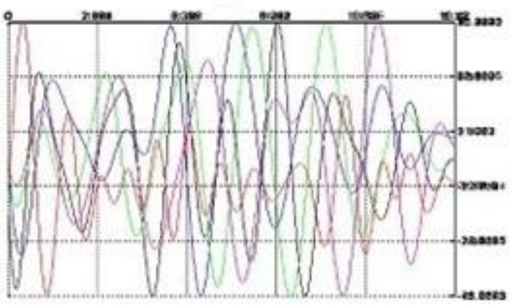
Figures 10 b: Normalized Velocity profile of Upper lip (UL) in Y axis for five participants in the Typical group



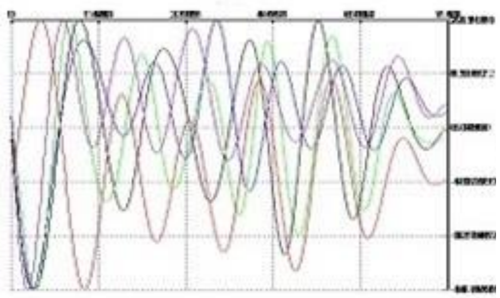
Figures11a: Normalized Velocity profile of Lower lip (LL) in Y axis for five participants in the Experimental group



Figures 11 b: Normalized Velocity profile of Lower lip (LL) in Y axis for five participants in the Typical group



Figures 12 a: Normalized Velocity profile of Jaw (J) in Y axis for five participants in the Experimental group



Figures12b: Normalized Velocity profile of Jaw (J)) in Y axis for five participants in the Typical group

Index: ■ = *E1, T1* ■ = *E2, T2* ■ = *E3, T3* ■ = *E4, T4* ■ = *E5, T5*

Note: UL = Upper Lip, LL = Lower Lip, J = Jaw E = Experimental group, T= Typical group, Amplitude = mm/s

B. Comparison of spatio-temporal indices (STIs) in the y – axis

Table 2

Spatio – temporal indices for the experimental and typical group of participants in the y – axis (superior-inferior dimension)

Experimental group	UL	LL	J	Typical group	UL	LL	J
E1	28.46	35.76	27.68	T1	38.04	24.85	23.89
E2	45.55	33.31	26.95	T2	34.00	17.63	19.02
E3	36.55	34.27	34.78	T3	23.26	26.46	28.00
E4	45.90	40.60	39.09	T4	16.72	19.88	35.87
E5	33.35	28.29	20.46	T5	43.09	23.11	26.92
Mean	37.96	34.44	29.79		31.02	22.38	26.74
Median	36.55	34.27	27.68		34.00	23.11	26.92
SD	7.65	4.43	7.26		10.82	8.60	6.17

Note: UL = Upper Lip, LL = Lower Lip, J = Jaw E = Experimental group, T= Typical group STI = Spatio-Temporal Index, SD = Standard deviation

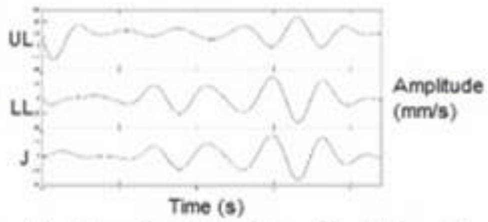
Comparison of mean STI across the experimental and typical group suggests that in general, the variability in speech motor control is relatively lesser in the typical participants compared to the experimental participants, as is evident from higher values of STI in the experimental group compared to the typical group. The STI of upper lip is higher in both the groups when compared to that of lower lip and jaw. The STI of the lower lip indicates a high variance compared to that of the typical group.

Data was subjected to statistical analysis (non parametric test) to test for the significance of the difference between the means of the two groups. Mann – Whitney U test was run to investigate the significant differences between the two groups for the mean STI of the upper lip, lower lip and jaw. The results revealed significant differences between the means of experimental and typical groups for the lower lip ($|Z|=2.61$, $p<0.05$).

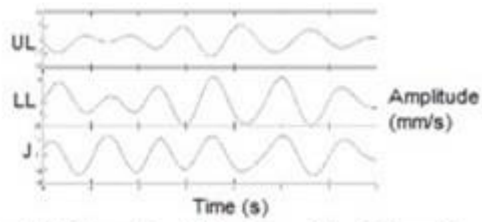
C. Comparison of velocity profiles across groups in the z – axis (anterior – posterior dimension)

The time and amplitude normalized velocity profiles of the experimental and typical group derived from the z axis are presented in Figures 13 (a & b) to Figures 17 (a & b). Comparison of Figures 13 a and b reveals that the time taken to produce the six iterations of /pa/ in the typical participant 1 was relatively lesser (7 seconds) than the experimental participant 1 (9 seconds). The wave morphology of the upper lip in the typical participant is indistinct for one instance of iteration, however, a clear coordination and phasic integrity is maintained across upper lip (UL), lower lip (LL) and jaw movements. In comparison to the typical participant, in the experimental participant, wave morphology was preserved only for 3 out of 6 iterations across the three cognate articulators. For the three peaks that are evident, good coordination and phasic differentiation is observed.

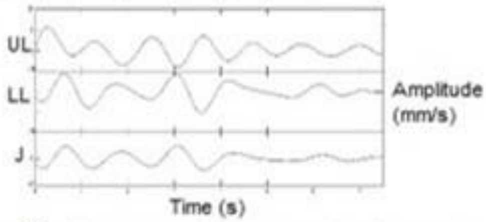
Findings from figures 14 a and b reveals that the experimental participant 2 took longer duration (7.5 seconds) in contrast to the typical participant (7 seconds). The amplitude of the waves for the six iterations in the lower lip and jaw traces are less robust and compromised in both the participants, but is preserved for the upper lip. It is probable that production of intelligible /pa/ utterences in both the participants is probably due to the compensated upper lip movement with little contribution from the lower lips and jaw.



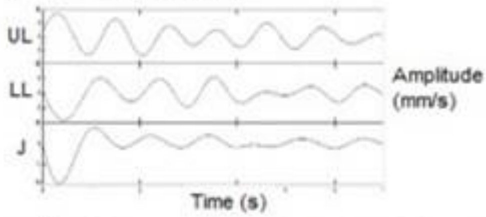
Figures 13 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 1 in Experimental group



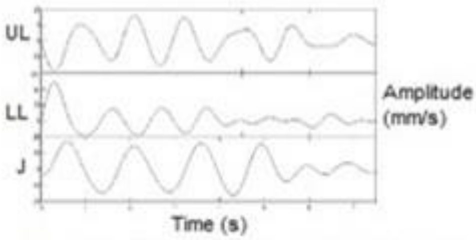
Figures 13 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 1 in Typical group



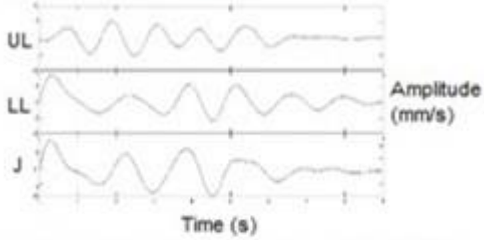
Figures 14 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 2 in Experimental group



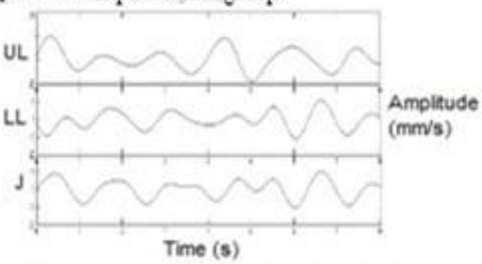
Figures 14 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 2 in Typical group



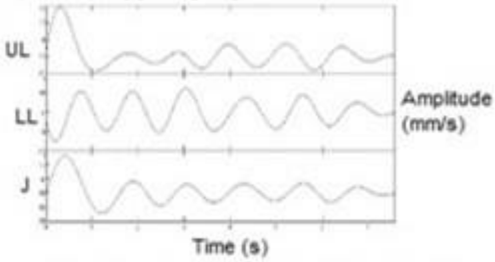
Figures 15 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 3 in Experimental group



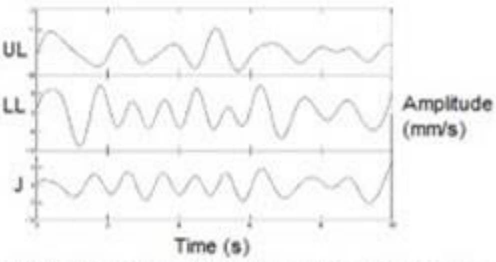
Figures 15 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 3 in Typical group



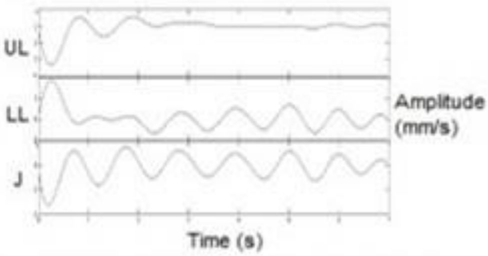
Figures 16 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 4 in Experimental group



Figures 16 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 4 in Typical group



Figures 17 a: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 4 in Experimental group



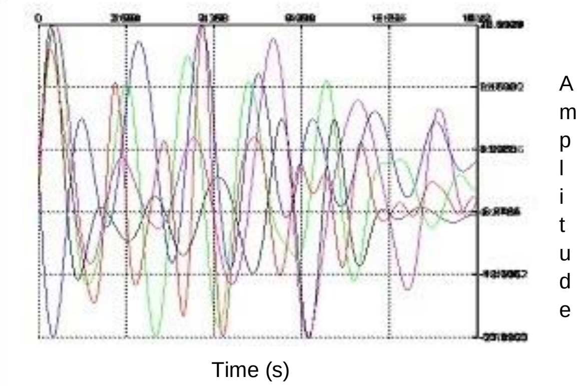
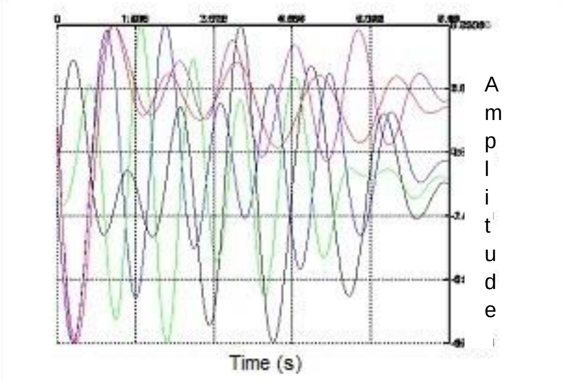
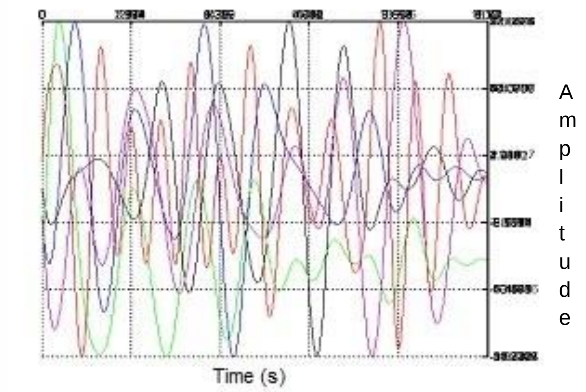
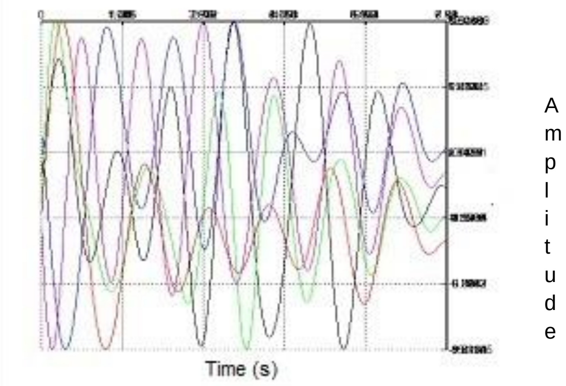
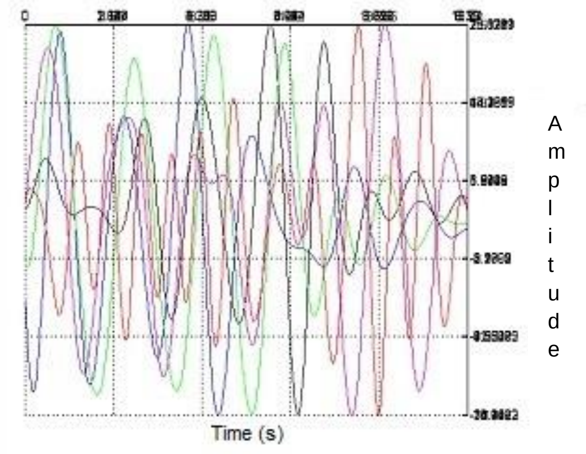
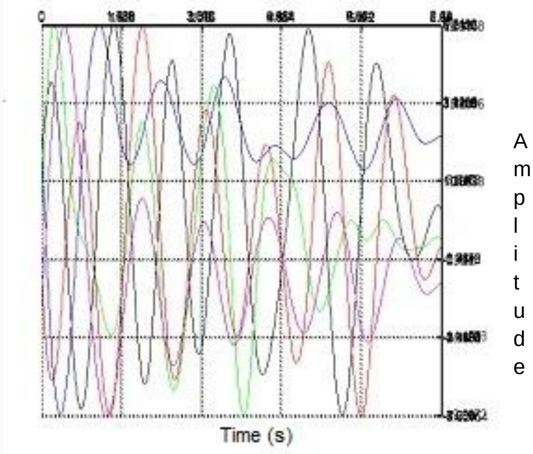
Figures 17 b: Normalized Velocity profile of Upper lip (UL), Lower lip (LL) and Jaw (J) in Z axis for Participant 4 in Typical group

From figure 15 a and b, it is observed that unlike the other four experimental participants, this participant showed a lesser duration (7.5 seconds) for the six iterations of /pa/ in contrast to the typical participant (9 seconds). The amplitude of the peaks was variable but with poor morphology across the three articulators in both the participants. Despite the poor morphology, lower lip and jaw exhibited good coordination in the typical participant. Phasic mismatch and poor coordinated movements were evident in the experimental participant in all the three articulators.

Comparison of the velocity profiles of the 4th pair of participants (Figures 16 a and b) reveals that the time taken by the experimental participant for the iterations of /pa/ syllables is prolonged (8 seconds) in comparison to that of the typical participant (7 seconds). The amplitudes of the peaks are more distinct in the typical participant, indicating a good wave morphology, except for the upper lip. The amplitude of the peaks are compromised in the experimental participant and the presence of indistinct multiple peaks suggest poor movement due to neuromotor involvement in this participant. Although not normal in terms of amplitude control, the coordination is maintained for the lower lip and jaw in both the participants.

Comparison of the velocity profiles in Figure 17 a and b reveals that the amplitude of movements across the three cognate articulators was reduced in the typical participant with evident coalescence in the upper lip movement. In the experimental participant, multipeaked amplitude for all the three articulators of upper lip, lower lip and jaw suggests an increased motoric effort in the anterior posterior dimensions while articulating the /pa syllable. The time taken by the experimental participant for the production of six iterations of /pa/ was also longer (10 seconds) than that of the typical participant. The less distinct waves in the typical participant, especially for the upper lip suggest a poor anterior posterior movement in the upper lip in this participant. This suggests that the lower lip and jaw movements have compensated in order to produce an intelligible /pa/. Although there is preserved coordination between the lower lip and jaw in both the participants, there is poor phasic integrity between the three articulators in these participants.

In summary, the analyses of results in the z axis (anterior to posterior dimension) indicate increased duration in the experimental group compared to the typical group (except for the third pair). All the 5 pairs of participants showed poor wave morphology in the anterior posterior dimension (z axis) for the utterance of /pa/ syllable when compared to the results seen for y axis (superior inferior dimension). However, the wave morphology of velocity profiles in typical participants were relatively robust with representative peaks for the iterated productions of /pa/ syllable (especially for the lower lip and jaw, except in the 2^{nd} and 3^{rd} pair). In the experimental group, except in the experimental participant 1 and 2, the velocity profiles of the UL and LL were not in phase and were not coordinated across the articulators. Both the groups showed a better coordination and phasic integrity for the LL and Jaw movements, compared to the upper lip. In comparison to the y – axis (superior – inferior dimension), the results of the z – axis (anterior – posterior dimension) exhibit higher variability. This means that speech motor stability as reflected by the velocity profiles was better in the superior-inferior dimensions of space (y axis) compared to the anterior-posterior dimensions of space (z axis). The points observed herewith are supported in the representation of group data for all the 5 participants of both the groups on a single plot [Figures 18 (a & b) to 20 (a & b)].

	
Figures 18 a: Normalized Velocity profile of Upper lip (UL) in Z axis for five participants in the Experimental group	*Figures 18 b:* Normalized Velocity profile of Upper lip (UL) in Z axis for five participants in the Typical group
	
Figures 19 a: Normalized Velocity profile of Lower lip (LL) in Z axis for five participants in the Experimental group	*Figures 19 b:* Normalized Velocity profile of Lower lip (LL) in Z axis for five participants in the Typical group
	
Figures20a: Normalized Velocity profile of Jaw (J) in Z axis for five participants in the Experimental group	*Figures20 b:* Normalized Velocity profile of Jaw (J) in Z axis for five participants in the Typical group

Index: ■ = *E1, T1* ■ = *E2, T2* ■ = *E3, T3* ■ = *E4, T4* ■ = *E5, T5*

Note: UL = Upper Lip, LL = Lower Lip, J = Jaw E = Experimental group, C= Typical group, Amplitude = mm/s

D. Comparison of spatio-temporal indices in the z – axis

Table 3

Spatio – temporal indices for the experimental and typical group of participants in the z – axis (anterior - posterior dimension)

Experimental group	UL	LL	J	Typical group	UL	LL	J
E1	45.45	35.07	36.52	T1	37.07	36.34	27.68
E2	45.88	28.61	29.07	T2	30.59	32.66	27.77
E3	43.06	26.10	19.72	T3	45.27	31.02	36.32
E4	45.30	43.82	44.32	T4	41.25	32.20	35.23
E5	39.38	28.41	37.43	T5	40.89	29.86	30.43
Mean STI	43.814	32.402	33.412		39.014	32.416	31.486
Median	36.52	45.30	28.61		30.43	40.89	32.20
SD	2.71	7.20	9.36		5.53	2.44	4.08

Note: UL = Upper Lip, LL = Lower Lip, J = Jaw E = Experimental group, T= Typical group STI = Spatio-Temporal Index, SD = Standard deviation

The mean STI is greater in the experimental group compared to the typical group except for the lower lip, suggesting a greater variability in speech motor control in the experimental group compared to the typical group. Mann – Whitney U test was carried out to verify if the differences in the mean for the upper lip, lower lip and jaw were significantly different across the two groups. The results revealed no significant differences across the three cognate articulators namely upper lip ($|Z|=1.17$; $p>0.05$), lower lip ($|Z|=0.73$; $p>0.05$) and jaw ($|Z|=0.94$; $p>0.05$) between the experimental and typical groups. This suggests that although the means for the upper lip and jaw was higher in the experimental group, it was not statistically significant.

The results are discussed in the following chapter

DISCUSSION

This study proposed to analyze and compare the kinematic traces of lip and jaw movements for the production of bilabial syllable /pa/ in isolation by typical children (Typical group) and children with spastic cerebral palsy (Experimental group) in the age range of 5 to 12 years, using *Wave Speech Research System* by Northern Digital Inc. (NDI), which is an electromagnetic non line – of – sight motion capture system. The results are presented under 4 heads in the previous chapter and the discussion is presented in the same order.

E. Comparison of velocity profiles across groups in the y – axis (superior - inferior dimension)

As may be seen from Figures 5 to 12, the salient findings were increased duration in the experimental participants (except for the fifth pair) with duration being more than that of the typical participants. Majority of the typical children showed good wave morphology with preserved peaks representative of the iterated productions of /pa/ syllable (except for the lower lip in typical participant 1 and upper lip in the typical participant 5). On the other hand, the velocity profiles of the UL, LL and Jaw were not in phase and this was also reflected in lack of coordination between these articulators in the experimental group (except participant 2). In some of the experimental participants (participants 4 and 5), the upper lip and lower lip did not show good peaks but the jaw movements were relatively preserved to represent the iterated movements.

The traces in the y axis represent the movements in the superior- inferior direction. The principle movement direction for the bilabial/pa/ syllable in the upper and lower lip with the jaw occurs in the superior and inferior direction and hence the traces in the y axis are very relevant to understand the motor primitive of these structures. The experimental group constituting of children with cerebral palsy (CP) have shown increased duration for the utterance chain of /pa syllables compared to the age and gender matched typical children. This result can be attributed to the deficient neuromotor control in these children as a result of brain insult as against a developing neuromotor system of the typical children. It may be postulated that there could be a temporal scale extension even in the typical children attributable to immature neuromotor system when compared to the mature adult system. However, the postulation cannot be generalized here because the adults were not included in the study. What is of salience is the finding of increased temporal scale in CP children compared to the typical children, which reveals that the kinematic analysis in this study was sensitive to reflect the poor speech motor control in the temporal dimension in these children which was affected due to neurogenic insult.

The amplitude peaks in the velocity profiles of typical children were distinct in terms of representing the up-down movement of the upper lip, lower lip and jaw for the 6 iterations that were analyzed. In comparison to this, the children with CP 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 /pa/ syllables. These point to a poor spatial integrity in the execution of up-down movement displacement by the lips and jaw. Over and above this factor, the figures from 5 to 9 also reveal a non phasic movement of the lips and jaw. It is known that the lower lip and the jaw move in phase and in the same direction (upwards and downwards), to facilitate production of /pa/ syllables. A good /pa/ sound can be produced only when the upper lip moves in the opposite direction and phase to that of the lower lip and jaw, which in turn leads to good coordinated movement for the target /pa/. This is seen to be reflected well in the traces of the typical children but not in that of CP children, where the traces indicate disturbed phasic movements and hence lack of coordination. Interestingly however, the participant 2 in the experimental group showed good phasic movement and this could be due to the focused articulation training that the child received in therapy. It was also observed that the amplitude peaks of the jaw were relatively distinct compared to the lower lip which were non distinct in most of the experimental participants except participant 2. This reveals that the jaw movement of gliding up and down was relatively preserved, but the lower lips which had to stretch to meet the upper lip in order to produce /pa/ syllable lacked the motor control. The mass of the jaw is higher than the lips and hence it is reported to have lower degrees of freedom for movements compared to the lower lip in an adult mature speech motor system. Keeping this in mind, it may be understood that the CP children have moved the jaw adequately but were less flexible in the movements of the lower lip to target the /pa/, which could be due to various inherent factors such as weakness of the lower lips or slow movements of the lower lips. This finding also suggests that the coordinate structures of lower lip and jaw have struck a motor balance (motor equivalence) as required for the target production of /pa/ by compensated movements of the jaw to meet the lacunae in the lower lip movements. It may thus be concluded that motor equivalence is attained even in the movements of children with cerebral palsy, as evidenced from the results of this study.

Studies have suggested that the jaw muscles are innervated by dense muscle spindles and thus provide a greater proprioceptive feedback and control (Schneider, 1987; Markham, 1987; Schneider et al., 1986). This could probably explain the lesser variability observed for the jaw movement in the velocity profiles which corresponds to lesser lower STI value compared to that of upper lip and lower lip.

Acquisition of speech motor control in children irrespective of whether it is typical children or children with cerebral palsy is influenced by the spurts of neuromotor maturation and growth in the anatomical structures involved in speech control. This is also described by the concept of ‘sensitivity period’, which refers to the time period where in a child learns a particular skill more easily than the others. This is a crucial process as it leads to mastery of various skills of motor act even including the act of producing the /pa syllable. It is reasonable to postulate that although both the groups of children (experimental and typical) would be under the influence of sensitivity period, a higher variability and instability that was evidenced based on the velocity profiles and STI measure in this study do point out that increased variability is a reflection of neuromotor insult which may be superimposed over and above the developmental factors in a maturing neuromotor system (as in typical children). Many factors contribute to the process of maturation during the sensitivity period. With relevance to this study, the most important factors are neural, non – linear developmental trend. The participants in the experimental group did have neurological insult leading to the condition of CP with musculoskeletal implications which influenced motor learning and refined control of a motor act such as production of /pa syllable/.

The motor act of speech is holistic and elements of movements to produce the target articulators are motor primitives reflecting the intended motor plan. Speech is a fine act that is controlled by distributed systems in the nervous system representing various areas with their interconnections which help in the execution of the speech act. It is reasonable to postulate that children with CP with evident neuromotor lesions in the brain are also under the influence of the distributed system and hence are able to produce speech sounds such as /pa/ syllable despite the lesion in specific loci of the brain. The influence of distributed system is such that it facilitates and promotes adaptive control strategies in the motor system to achieve the target function. The influence of adaptive control is true in typically developing children as well as children with CP. An adult neuromotor system is characterized by high adaptive control, but in children, the plasticity to achieve this control is an ongoing – process. In children with cerebral palsy, because of the underlying neurological insult, it can be understood that adaptive control is not equivalent to that of a typical child. This in turn gets reflected in the measures of variability such as velocity profiles and STIs as derived in this study.

Thelen and Smith (1994) also observed that in typical children, the plasticity and the adaptive control is yet to mature and are in weak attractor states which gets reflected in the highly variable speech motor control reflected as higher STIs. The results observed for typical group in this study is in agreement with this observation.

The results of the typical children of this study are also in agreement with other studies which reported that in comparison to adults, children showed more variable amplitude, velocity, timing and patterning of articulatory movements in the upper lip, lower lip and jaw as evidenced through kinematic analyses (Goffman & Smith, 1999; Green, Moore & Reilly, 2002; Green, Moore, Higashikawa & Steeve, 2000; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean – Muse, 1986; Smith & Zelaznik, 2004; Walsh & Smith, 2002).

F. Comparison of spatio-temporal indices (STIs) in the y – axis

The spatio-temporal indices are reflections of integrity in the spatial and temporal control for a given movement. Ideally, stability of motor control in speech would be a value less that a unit, if and only when the coordinative movements of given set of articulators are in phase performed within an expected time frame. Mature control of speech motor system is reported to occur only by 14 years of age (Kent, 1976; Goffman & Smith, 1999; Green, Moore, Higashikawa & Steeve, 2000; Yan 2007). The mean values of STI for the upper lip, lower lip and jaw in the typical group were 31.00, 22.38 and 26.74 respectively. In comparison, the mean values of STI for the upper lip, lower lip and jaw in the experiment group was 37.96, 34.44 and 29.79 respectively. The mean STIs in the experimental group were greater than that of the typical group for all the articulators, suggesting a greater variance in the motor control of the articulators in the experimental group. Statistically however, the difference was found to be significant only for the lower lip ($|Z|=2.61$, $p<0.05$). This defies the hypothesis of this study as the STI values clearly indicate that variance in speech motor control has been higher in the experimental group compared to the typical group. This also supports the justification of the study that variance will be greater in experimental group with neuromotor lesions compared to the variance seen in the developing neuromotor system of the typical group.

The motor program theory (Schmidt, 1976, 1982), suggests 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, when spatial dimensions are disturbed, rescaling /compensation occurs in the temporal dimension and vice versa. The act of achieving a motor balance as expected for a target sound utterance is explained as 'motor equivalence'. The rescaling was evident in the amplitude and time trade-offs as seen in the velocity profiles derived in this study. This seemed to be more evident in the experimental group compared to the typical group as the children with CP did produce a good acoustically acceptable /pa syllable (which was also one of the inclusionary criteria for subject selection) but the wave morphology and amplitude peaks of the velocity profiles were not good and the temporal durations were increased.

The higher values of STI for upper lip, lower lip and jaw in the typical group of children is similar to the results reported in earlier studies (Goffman & Smith, 1999; Green, Moore & Reilly, 2002; Green, Moore, Higashikawa & Steeve, 2000; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean – Muse, 1986; Smith &Zelaznik, 2004;

Walsh & Smith, 2002), which was stated to be a reflection of ongoing process of maturation and refinement of the speech motor control system.

G. Comparison of velocity profiles across groups in the z – axis (anterior – posterior dimension)

The traces in the z axis reveal the information about the anterior posterior dimension of movements during the production of the bilabial /pa/ syllable. Although the bilabial sounds are principally characterized by the superior and inferior movements (as captured in the y axis), it is known that translation angles of the movements such as anterior-posterior movements are also important and needs to be understood. The movement of the upper lip, lower lip and jaw in the anterior-posterior direction as reflected in the z axis would be far less than that of the y axis which depicts the superior-inferior dimensions of movement for /pa syllable. In this study however, since the scale selected for the temporal and the spatial dimensions were the same and because the results of the y and z axis was not represented in the same graph, the differences with respect to the peaks in the amplitude curve for y and z axis has not been reflected diagrammatically. However, it may be noted that the inferences are drawn based on the amplitude values only in the velocity profiles.

The analyses of results in the z axis (anterior to posterior dimension) indicate increased duration in the experimental group compared to the typical group (except for the third pair). All the 5 pairs of participants showed poor wave morphology in the anterior posterior dimension (z axis) for the utterance of /pa/ syllable when compared to the results seen for y axis (superior inferior dimension). This suggests that although the anterior posterior movements could be occurring to a minimal extent to bring in precision of motor control as required for /pa/ syllable utterance, they were more affected than that of up-down movement of the lips and jaw. In other words, it may also be stated that the children with CP seemed to lack precise motor control over production of /pa/ syllable in the translation angles such as z axis when compared to the y axis which serves as the principle angle of movement of the bilabial sounds. It would be of interest to follow this postulation by studying the performance in the x axis also which reflects on the translated angle movement of medial-lateral dimensions in future studies, but this was not analyzed in this study. In comparison to the y – axis (superior – inferior dimension), the results of the z – axis (anterior – posterior dimension) exhibited higher variability. This means that speech motor stability as reflected by the velocity profiles was better in the superior-inferior dimensions of space (y axis) compared to the anterior-posterior dimensions of space (z axis).

Further, the results of z axis revealed that the wave morphology of velocity profiles in typical participants were relatively robust with representative peaks for the iterated productions of /pa/ syllable (especially for the lower lip and jaw, except in the 2nd and 3rd pair of participants). In the experimental group, except in the experimental participant 1 and 2, the velocity profiles of the UL and LL were not in phase and were not coordinated across the articulators. Both the groups showed a better coordination and phasic integrity for the LL and Jaw movements, compared to the upper lip.

In one of the participant from the experimental group, multiple velocity peaks were observed. Similar findings have been reported in slow velocity hand movements (Milner, 1989; Milner & Ijaz, 1990) for the task of placing peg holes of varying diameter. According to the 'Error Correction Model' of motor control, Milner (1989) explains that the multiple peaks reflect a sequence of overlapping sub movements that are used to make precise spatial and temporal adjustments over the course of a movement. Thus, for movements in which the spatial accuracy demands remain the same, multiple sub - movements could have been used as a motor control strategy to achieve accurate output by these children with CP.

In another typical participant, there were very minimal peaks in the velocity profile of upper lip. Labial rigidity could also be a factor limiting the movements of the lips, which in turn were reflected in the velocity profiles and STIs. In this study, there seemed to be increased stiffness in the upper lip of the children with CP in comparison to the lower lip, as reflected in most of the velocity traces.

H. Comparison of spatio-temporal indices in the z – axis

The mean STIs of z axis were greater in the experimental group (43.81,32.40 & 33.41 for upper lip, lower lip and jaw respectively) compared to the typical group (39.01, 32.41 & 31.48 for upper lip, lower lip and jaw respectively) except for the lower lip, suggesting a greater variability in speech motor control in the experimental group compared to the typical group. Statistically however, the difference were not found to be significant across the groups for the articulators namely upper lip ($|Z|=1.17$; $p>0.05$), lower lip ($|Z|=0.73$; $p>0.05$) and jaw ($|Z|=0.94$; $p>0.05$).

Similar to the results obtained for the y axis, the results point to increased variability in the children with CP (with neuromotor deficit) compared to typical children (with yet to mature neuromotor system). This defies the hypothesis of the study as the STI values clearly indicate that variance in speech motor control has been higher in the experimental group compared to the typical group.

In summary, the hypothesis of the study which stated that there would be no significant difference in the velocity profiles and spatio – temporal indices (STI) of upper lip, lower lip and jaw for the production of iterated /pa/ syllable between the typical and experimental group is defied. There was evident variability in typical as well as experimental group. The variance was higher in children with CP (experimental group) compared to the typical group of children.

SUMMARY AND CONCLUSION

The aim of this study was to analyse and compare the kinematic traces of lips and jaw for the bilabial sound /pa/ in isolation in children with spastic cerebral palsy and age and gender matched typical children in the age range of 5 to 12 years. This was a preliminary attempt made to analyse the speech motor control and to understand the difference in the variability/ instability seen across the two groups using *Wave Speech Research System* designed by Northern Digital Inc. (NDI), which is an electromagnetic non – line – of – sight motion capture system. The objectives included the analysis and comparison of the velocity profiles and the Spatio – Temporal Indices (STIs) of the upper lip, lower lip and jaw in the y – axis (superior – inferior dimension) and the z – axis (anterior – posterior dimension).

Five children with spastic cerebral palsy and five age and gender matched typical children were included and the kinematic traces of the upper lip, lower lip and jaw were obtained using 4 channels (4 sensors:3 test sensors on upper lip, lower lip and jaw and one reference sensor on the jaw) with a resolution of five degrees of freedom (5 DOF) in 500 mm cube field in the Wave Speech Research System. The appropriateness of the position data recorded on the wave speech research system was visualized using VisArtico software (Version V.0.9.9 - February 2015) and the data was analyzed using the MATLAB script of the Speech Movement Analysis, Statistics and Histograms (SMASH) tool (version 0.6) developed by Greene, Wang and Wilson (2013). Of the 12 iterations of /pa/ syllable in isolation produced by each participant of the two groups, the middle 6 iterations were selected to rule out onset and offset effects of motor activity. The data of the 6 iterations was used to estimate the velocity profiles and Spatio Temporal Indices (STI) for each of the articulators, namely, upper lip, lower lip and jaw, per participant in the y axis (depicting the superior-inferior movement dimension) and z axis (depicting the anterior-posterior movement dimension).

The results were presented and discussed under the following sections:

E. Comparison of velocity profiles across groups in the y – axis (superior - inferior dimension)
F. Comparison of spatio - temporal indices across groups in the y – axis (superior - inferior dimension)
G. Comparison of velocity profiles across groups in the z – axis (anterior – posterior dimension)
H. Comparison of spatio - temporal indices across groups in the z – axis (anterior – posterior dimension)

The velocity profiles derived in the y – axis (superior – inferior dimension) revealed increased duration in children with cerebral palsy compared to the typical group of children. The wave morphology showed prominent peaks of the iterated bilabial /pa/ syllable in typical group (except for the lower lip in typical participant 1 and upper lip in the typical participant 5). Lack of coordination and disintegrity in phasic movements (except in the experimental participant 2), was seen in the velocity profiles for the upper lip, lower lip and jaw in the experimental group. In the experimental participants 4 and 5, the upper lip and lower lip did not show good peaks but the jaw movements were relatively preserved to represent the iterated movements of /pa/. Although the mean STI for all the three articulators indicated higher variability in the experimental group compared to the typical group, it was found to be statistically significant for the lower lip only ($|Z|=2.61$, $p<0.05$) .

Analyses of the velocity profiles in the z – axis (anterior – posterior dimension) also revealed increased duration in the experimental group compared to the typical group (except in the third pair of participants). The findings revealed that both the groups showed poor wave morphology with typical participants having relatively distinct peaks representative of the iterated productions of /pa/ syllable (especially for the lower lip and jaw, except in the 2^{nd} and 3^{rd} pair). Both the groups showed a better coordination and phasic integrity for the LL and Jaw movements. In contrast to the y – axis (superior – inferior dimension), the results of the z – axis (anterior – posterior dimension) exhibited greater instability. The mean STI of the articulators were higher in the experimental group compared to the typical group, but statistically, the difference was not found to be significant for upper lip ($|Z|=1.17$; $p>0.05$), lower lip ($|Z|=0.73$; $p>0.05$) and jaw ($|Z|=0.94$; $p>0.05$).

In summary, the hypothesis of the study which stated that there would be no significant difference in the velocity profiles and spatio – temporal indices (STI) of upper lip, lower lip and jaw for the production of iterated /pa/ syllable between the typical and experimental group is defied. There was evident variability in typical as well as experimental group. The variance was higher in children with CP (experimental group) compared to the typical group of children.

Future directions

1. The present study is one of the preliminary attempts made to compare the velocity profiles and spatio – temporal indices for iterated /pa/ syllable production in isolation across children with cerebral palsy and typical children. Research needs to be carried to study the influence of context, age, subtype of cerebral palsy and type of training in articulation on the velocity profiles and STI in children with cerebral palsy
2. The experimental paradigm in this study can be used to address the speech motor characteristics in children with phonological disorder/stuttering/apraxia of speech.

DISCUSSION

This study proposed to analyze and compare the kinematic traces of lip and jaw movements for the production of bilabial syllable /pa/ in isolation by typical children (Typical group) and children with spastic cerebral palsy (Experimental group) in the age range of 5 to 12 years, using *Wave Speech Research System* by Northern Digital Inc. (NDI), which is an electromagnetic non line – of – sight motion capture system. The results are presented under 4 heads in the previous chapter and the discussion is presented in the same order.

A. Comparison of velocity profiles across groups in the y – axis (superior - inferior dimension)

As may be seen from Figures 5 to 12, the salient findings were increased duration in the experimental participants (except for the fifth pair) with duration being more than that of the typical participants. Majority of the typical children showed good wave morphology with preserved peaks representative of the iterated productions of /pa/ syllable (except for the lower lip in typical participant 1 and upper lip in the typical participant 5). On the other hand, the velocity profiles of the UL, LL and Jaw were not in phase and this was also reflected in lack of coordination between these articulators in the experimental group (except participant 2). In some of the experimental participants (participants 4 and 5), the upper lip and lower lip did not show good peaks but the jaw movements were relatively preserved to represent the iterated movements.

The traces in the y axis represent the movements in the superior- inferior direction. The principle movement direction for the bilabial/pa/ syllable in the upper and lower lip with the jaw occurs in the superior and inferior direction and hence the traces in the y axis are very relevant to understand the motor primitive of these structures. The experimental group constituting of children with cerebral palsy (CP) have shown increased duration for the utterance chain of /pa syllables compared to the age and gender matched typical children. This result can be attributed to the deficient neuromotor control in these children as a result of brain insult as against a developing neuromotor system of the typical children. It may be postulated that there could be a temporal scale extension even in the typical children attributable to immature neuromotor system when compared to the mature adult system. However, the postulation cannot be generalized here because the adults were not included in the study. What is of salience is the finding of increased temporal scale in CP children compared to the typical children, which reveals that the kinematic analysis in this study was sensitive to reflect the poor speech motor control in the temporal dimension in these children which was affected due to neurogenic insult.

The amplitude peaks in the velocity profiles of typical children were distinct in terms of representing the up-down movement of the upper lip, lower lip and jaw for the 6 iterations that were analyzed. In comparison to this, the children with CP 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 /pa/ syllables. These point to a poor spatial integrity in the execution of up-down movement displacement by the lips and jaw. Over and above this factor, the figures from 5 to 9 also reveal a non phasic movement of the lips and jaw. It is known that the lower lip and the jaw move in phase and in the same direction (upwards and downwards), to facilitate production of /pa/ syllables. A good /pa/ sound can be produced only when the upper lip moves in the opposite direction and phase to that of the lower lip and jaw, which in turn leads to good coordinated movement for the target /pa/. This is seen to be reflected well in the traces of the typical children but not in that of CP children, where the traces indicate disturbed phasic movements and hence lack of coordination. Interestingly however, the participant 2 in the experimental group showed good phasic movement and this could be due to the focused articulation training that the child received in therapy. It was also observed that the amplitude peaks of the jaw were relatively distinct compared to the lower lip which were non distinct in most of the experimental participants except participant 2. This reveals that the jaw movement of gliding up and down was relatively preserved, but the lower lips which had to stretch to meet the upper lip in order to produce /pa/ syllable lacked the motor control. The mass of the jaw is higher than the lips and hence it is reported to have lower degrees of freedom for movements compared to the lower lip in an adult mature speech motor system. Keeping this in mind, it may be understood that the CP children have moved the jaw adequately but were less flexible in the movements of the lower lip to target the /pa/, which could be due to various inherent factors such as weakness of the lower lips or slow movements of the lower lips. This finding also suggests that the coordinate structures of lower lip and jaw have struck a motor balance (motor equivalence) as required for the target production of /pa/ by compensated movements of the jaw to meet the lacunae in the lower lip movements. It may thus be concluded that motor equivalence is attained even in the movements of children with cerebral palsy, as evidenced from the results of this study.

Studies have suggested that the jaw muscles are innervated by dense muscle spindles and thus provide a greater proprioceptive feedback and control (Schneider, 1987; Markham, 1987; Schneider et al., 1986). This could probably explain the lesser variability observed for the jaw movement in the velocity profiles which corresponds to lesser lower STI value compared to that of upper lip and lower lip.

Acquisition of speech motor control in children irrespective of whether it is typical children or children with cerebral palsy is influenced by the spurts of neuromotor maturation and growth in the anatomical structures involved in speech control. This is also described by the concept of ‘sensitivity period’, which refers to the time period where in a child learns a particular skill more easily than the others. This is a crucial process as it leads to mastery of various skills of motor act even including the act of producing the /pa syllable. It is reasonable to postulate that although both the groups of children (experimental and typical) would be under the influence of sensitivity period, a higher variability and instability that was evidenced based on the velocity profiles and STI measure in this study do point out that increased variability is a reflection of neuromotor insult which may be superimposed over and above the developmental factors in a maturing neuromotor system (as in typical children). Many factors contribute to the process of maturation during the sensitivity period. With relevance to this study, the most important factors are neural, non – linear developmental trend. The participants in the experimental group did have neurological insult leading to the condition of CP with musculoskeletal implications which influenced motor learning and refined control of a motor act such as production of /pa syllable/.

The motor act of speech is holistic and elements of movements to produce the target articulators are motor primitives reflecting the intended motor plan. Speech is a fine act that is controlled by distributed systems in the nervous system representing various areas with their interconnections which help in the execution of the speech act. It is reasonable to postulate that children with CP with evident neuromotor lesions in the brain are also under the influence of the distributed system and hence are able to produce speech sounds such as /pa/ syllable despite the lesion in specific loci of the brain. The influence of distributed system is such that it facilitates and promotes adaptive control strategies in the motor system to achieve the target function. The influence of adaptive control is true in typically developing children as well as children with CP. An adult neuromotor system is characterized by high adaptive control, but in children, the plasticity to achieve this control is an ongoing – process. In children with cerebral palsy, because of the underlying neurological insult, it can be understood that adaptive control is not equivalent to that of a typical child. This in turn gets reflected in the measures of variability such as velocity profiles and STIs as derived in this study.

Thelen and Smith (1994) also observed that in typical children, the plasticity and the adaptive control is yet to mature and are in weak attractor states which gets reflected in the highly variable speech motor control reflected as higher STIs. The results observed for typical group in this study is in agreement with this observation.

The results of the typical children of this study are also in agreement with other studies which reported that in comparison to adults, children showed more variable amplitude, velocity, timing and patterning of articulatory movements in the upper lip, lower lip and jaw as evidenced through kinematic analyses (Goffman & Smith, 1999; Green, Moore & Reilly, 2002; Green, Moore, Higashikawa & Steeve, 2000; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean – Muse, 1986; Smith & Zelaznik, 2004; Walsh & Smith, 2002).

B. Comparison of spatio-temporal indices (STIs) in the y – axis

The spatio-temporal indices are reflections of integrity in the spatial and temporal control for a given movement. Ideally, stability of motor control in speech would be a value less that a unit, if and only when the coordinative movements of given set of articulators are in phase performed within an expected time frame. Mature control of speech motor system is reported to occur only by 14 years of age (Kent, 1976; Goffman & Smith, 1999; Green, Moore, Higashikawa & Steeve, 2000; Yan 2007). The mean values of STI for the upper lip, lower lip and jaw in the typical group were 31.00, 22.38 and 26.74 respectively. In comparison, the mean values of STI for the upper lip, lower lip and jaw in the experiment group was 37.96, 34.44 and 29.79 respectively. The mean STIs in the experimental group were greater than that of the typical group for all the articulators, suggesting a greater variance in the motor control of the articulators in the experimental group. Statistically however, the difference was found to be significant only for the lower lip ($|Z|=2.61$, $p<0.05$). This defies the hypothesis of this study as the STI values clearly indicate that variance in speech motor control has been higher in the experimental group compared to the typical group. This also supports the justification of the study that variance will be greater in experimental group with neuromotor lesions compared to the variance seen in the developing neuromotor system of the typical group.

The motor program theory (Schmidt, 1976, 1982), suggests 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, when spatial dimensions are disturbed, rescaling /compensation occurs in the temporal dimension and vice versa. The act of achieving a motor balance as expected for a target sound utterance is explained as ‘motor equivalence’. The rescaling was evident in the amplitude and time trade-offs as seen in the velocity profiles derived in this study. This seemed to be more evident in the experimental group compared to the typical group as the children with CP did produce a good acoustically acceptable /pa syllable (which was also one of the inclusionary criteria for subject selection) but the wave morphology and amplitude peaks of the velocity profiles were not good and the temporal durations were increased.

The higher values of STI for upper lip, lower lip and jaw in the typical group of children is similar to the results reported in earlier studies (Goffman & Smith, 1999; Green, Moore & Reilly, 2002; Green, Moore, Higashikawa & Steeve, 2000; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean – Muse, 1986; Smith &Zelaznik, 2004; Walsh & Smith, 2002), which was stated to be a reflection of ongoing process of maturation and refinement of the speech motor control system.

C. Comparison of velocity profiles across groups in the z – axis (anterior – posterior dimension)

The traces in the z axis reveal the information about the anterior posterior dimension of movements during the production of the bilabial /pa/ syllable. Although the bilabial sounds are principally characterized by the superior and inferior movements (as captured in the y axis), it is known that translation angles of the movements such as anterior-posterior movements are also important and needs to be understood. The movement of the upper lip, lower lip and jaw in the anterior-posterior direction as reflected in the z axis would be far less than that of the y axis which depicts the superior-inferior dimensions of movement for /pa syllable. In this study however, since the scale selected for the temporal and the spatial dimensions were the same and because the results of the y and z axis was not represented in the same graph, the differences with respect to the peaks in the amplitude curve for y and z axis has not been reflected diagrammatically. However, it may be noted that the inferences are drawn based on the amplitude values only in the velocity profiles.

The analyses of results in the z axis (anterior to posterior dimension) indicate increased duration in the experimental group compared to the typical group (except for the third pair). All the 5 pairs of participants showed poor wave morphology in the anterior posterior dimension (z axis) for the utterance of /pa/ syllable when compared to the results seen for y axis (superior inferior dimension). This suggests that although the anterior posterior movements could be occurring to a minimal extent to bring in precision of motor control as required for /pa/ syllable utterance, they were more affected than that of up-down movement of the lips and jaw. In other words, it may also be stated that the children with CP seemed to lack precise motor control over production of /pa/ syllable in the translation angles such as z axis when compared to the y axis which serves as the principle angle of movement of the bilabial sounds. It would be of interest to follow this postulation by studying the performance in the x axis also which reflects on the translated angle movement of medial-lateral dimensions in future studies, but this was not analyzed in this study. In comparison to the y – axis (superior – inferior dimension), the results of the z – axis (anterior – posterior dimension) exhibited higher variability. This means that speech motor stability as reflected by the velocity profiles was better in the superior-inferior dimensions of space (y axis) compared to the anterior-posterior dimensions of space (z axis).

Further, the results of z axis revealed that the wave morphology of velocity profiles in typical participants were relatively robust with representative peaks for the iterated productions of /pa/ syllable (especially for the lower lip and jaw, except in the 2nd and 3rd pair of participants). In the experimental group, except in the experimental participant 1 and 2, the velocity profiles of the UL and LL were not in phase and were not coordinated across the articulators. Both the groups showed a better coordination and phasic integrity for the LL and Jaw movements, compared to the upper lip.

In one of the participant from the experimental group, multiple velocity peaks were observed. Similar findings have been reported in slow velocity hand movements (Milner, 1989; Milner & Ijaz, 1990) for the task of placing peg holes of varying diameter. According to the ‘Error Correction Model’ of motor control, Milner (1989) explains that the multiple peaks reflect a sequence of overlapping sub movements that are used to make precise spatial and temporal adjustments over the course of a movement. Thus, for movements in which the spatial accuracy demands remain the same, multiple sub - movements could have been used as a motor control strategy to achieve accurate output by these children with CP.

In another typical participant, there were very minimal peaks in the velocity profile of upper lip. Labial rigidity could also be a factor limiting the movements of the lips, which in turn were reflected in the velocity profiles and STIs. In this study, there seemed to be increased stiffness in the upper lip of the children with CP in comparison to the lower lip, as reflected in most of the velocity traces.

D. Comparison of spatio-temporal indices in the z – axis

The mean STIs of z axis were greater in the experimental group (43.81,32.40 & 33.41 for upper lip, lower lip and jaw respectively) compared to the typical group (39.01, 32.41 & 31.48 for upper lip, lower lip and jaw respectively) except for the lower lip, suggesting a greater variability in speech motor control in the experimental group compared to the typical group. Statistically however, the difference were not found to be significant across the groups for the articulators namely upper lip ($|Z|=1.17$; $p>0.05$), lower lip ($|Z|=0.73$; $p>0.05$) and jaw ($|Z|=0.94$; $p>0.05$).

Similar to the results obtained for the y axis, the results point to increased variability in the children with CP (with neuromotor deficit) compared to typical children (with yet to mature neuromotor system). This defies the hypothesis of the study as the STI values clearly indicate that variance in speech motor control has been higher in the experimental group compared to the typical group.

In summary, the hypothesis of the study which stated that there would be no significant difference in the velocity profiles and spatio – temporal indices (STI) of upper lip, lower lip and jaw for the production of iterated /pa/ syllable between the typical and experimental group is defied. There was evident variability in typical as well as experimental group. The variance was higher in children with CP (experimental group) compared to the typical group of children.

SUMMARY AND CONCLUSION

The aim of this study was to analyse and compare the kinematic traces of lips and jaw for the bilabial sound /pa/ in isolation in children with spastic cerebral palsy and age and gender matched typical children in the age range of 5 to 12 years. This was a preliminary attempt made to analyse the speech motor control and to understand the difference in the variability/ instability seen across the two groups using *Wave Speech Research System* designed by Northern Digital Inc. (NDI), which is an electromagnetic non – line – of – sight motion capture system. The objectives included the analysis and comparison of the velocity profiles and the Spatio – Temporal Indices (STIs) of the upper lip, lower lip and jaw in the y – axis (superior – inferior dimension) and the z – axis (anterior – posterior dimension).

Five children with spastic cerebral palsy and five age and gender matched typical children were included and the kinematic traces of the upper lip, lower lip and jaw were obtained using 4 channels (4 sensors:3 test sensors on upper lip, lower lip and jaw and one reference sensor on the jaw) with a resolution of five degrees of freedom (5 DOF) in 500 mm cube field in the Wave Speech Research System. The appropriateness of the position data recorded on the wave speech research system was visualized using VisArtico software (Version V.0.9.9 - February 2015) and the data was analyzed using the MATLAB script of the Speech Movement Analysis, Statistics and Histograms (SMASH) tool (version 0.6) developed by Greene, Wang and Wilson (2013). Of the 12 iterations of /pa/ syllable in isolation produced by each participant of the two groups, the middle 6 iterations were selected to rule out onset and offset effects of motor activity. The data of the 6 iterations was used to estimate the velocity profiles and Spatio Temporal Indices (STI) for each of the articulators, namely, upper lip, lower lip and jaw, per participant in the y axis (depicting the superior-inferior movement dimension) and z axis (depicting the anterior-posterior movement dimension).

The results were presented and discussed under the following sections:

A. Comparison of velocity profiles across groups in the y – axis (superior - inferior dimension)
B. Comparison of spatio - temporal indices across groups in the y – axis (superior - inferior dimension)
C. Comparison of velocity profiles across groups in the z – axis (anterior – posterior dimension)
D. Comparison of spatio - temporal indices across groups in the z – axis (anterior – posterior dimension)

The velocity profiles derived in the y – axis (superior – inferior dimension) revealed increased duration in children with cerebral palsy compared to the typical group of children. The wave morphology showed prominent peaks of the iterated bilabial /pa/ syllable in typical group (except for the lower lip in typical participant 1 and upper lip in the typical participant 5). Lack of coordination and disintegrity in phasic movements (except in the experimental participant 2), was seen in the velocity profiles for the upper lip, lower lip and jaw in the experimental group. In the experimental participants 4 and 5, the upper lip and lower lip did not show good peaks but the jaw movements were relatively preserved to represent the iterated movements of /pa/. Although the mean STI for all the three articulators indicated higher variability in the experimental group compared to the typical group, it was found to be statistically significant for the lower lip only ($|Z|=2.61$, $p<0.05$) .

Analyses of the velocity profiles in the z – axis (anterior – posterior dimension) also revealed increased duration in the experimental group compared to the typical group (except in the third pair of participants). The findings revealed that both the groups showed poor wave morphology with typical participants having relatively distinct peaks representative of the iterated productions of /pa/ syllable (especially for the lower lip and jaw, except in the 2nd and 3rd pair). Both the groups showed a better coordination and phasic integrity for the LL and Jaw movements. In contrast to the y – axis (superior – inferior dimension), the results of the z – axis (anterior – posterior dimension) exhibited greater instability. The mean STI of the articulators were higher in the experimental group compared to the typical group, but statistically, the difference was not found to be significant for upper lip ($|Z|=1.17$; $p>0.05$), lower lip ($|Z|=0.73$; $p>0.05$) and jaw ($|Z|=0.94$; $p>0.05$).

In summary, the hypothesis of the study which stated that there would be no significant difference in the velocity profiles and spatio – temporal indices (STI) of upper lip, lower lip and jaw for the production of iterated /pa/ syllable between the typical and experimental group is defied. There was evident variability in typical as well as experimental group. The variance was higher in children with CP (experimental group) compared to the typical group of children.

Future directions

1. The present study is one of the preliminary attempts made to compare the velocity profiles and spatio – temporal indices for iterated /pa/ syllable production in isolation across children with cerebral palsy and typical children. Research needs to be carried to study the influence of context, age, subtype of cerebral palsy and type of training in articulation on the velocity profiles and STI in children with cerebral palsy
2. The experimental paradigm in this study can be used to address the speech motor characteristics in children with phonological disorder/stuttering/apraxia of speech.

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