Kinematic changes in jaw and lip control of children with cerebral palsy following participation in a motor-speech (PROMPT) intervention.

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Abstract

This study evaluates kinematic movements of the jaw and lips in six children (3-to-11 years) with moderate-to-severe speech impairment associated with cerebral palsy before, during and after participation in a motor-speech (PROMPT) intervention program. An ABCA single subject research design was implemented. Subsequent to the baseline phase (A), phase B targeted each participant's first intervention priority on the PROMPT motor-speech hierarchy. Phase C then targeted one level higher. A reference group of twelve typically-developing peers, age-and sex-matched to each participant with CP, was recruited for comparison in the interpretation of the kinematic data. Jaw and lip measurements of distance, velocity and duration, during the production of 11 untrained stimulus words, were obtained at the end of each study phase using 3D motion analysis (Vicon Motus 9. 1). All participants showed significant changes in specific movement characteristics of the jaw and lips. Kinematic changes were associated with significant positive changes to speech intelligibility in five of the six participants. This study makes a contribution to providing evidence that supports the use of a treatment approach aligned with dynamic systems theory to improve the motor-speech movement patterns and speech intelligibility in children with cerebral palsy.

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Cerebral palsy (CP) is a neurodevelopmental condition that includes a group of non-progressive movement and posture disorders that are a result of lesions or dysfunction to the central nervous system. Impairments associated with CP include disturbances of sensation, cognition, behaviour, language and speech (Rosenbaum, Paneth, Leviton, Goldstein, & Bax, 2007).

Whilst the most commonly reported speech impairment associated with cerebral palsy (CP) is dysarthria (Hodge & Wellman, 1999; Pennington, Miller, & Robson, 2009), recent work has suggested that even children who do not present with explicit symptoms of dysarthric speech may experience underlying motor control deficits (Hustad, Gorton, & Lee, 2010).

The motor speech impairments associated with CP may impact an individual's ability to produce speech efficiently and accurately, due to impairments in timing and coordination across the speech subsystems. The literature describes impairment to different subsystems of speech control including respiration, phonation, resonance and articulation. Reduced speech intelligibility has been associated with poor breath quality, inappropriate voicing, slower speech rate, reduced vowel space, excessive or reduced movements and articulatory imprecision (Hustad, et al., 2010; Lin, Chen, & Lee, 2007; Soloman & Charron, 1998; Workinger, 2005). Whilst the Mayo classification system has been used to describe the perceptual characteristics observed in children with dysarthria, more recent research indicates classification on the basis of severity and disease type may be more appropriate (Kim, Kent, & Weismer, 2011).

Speech subsystems coordination

Coordination of the speech subsystems involves precise, rapid and complex goal-oriented behaviours with many potential degrees of freedom of movement. For example, the motion of the mandible is characterised by three orientation angles and three positions (Ostry, Vatikiotis-Bateson, & Gribble, 1997). The lips and tongue have limitless possibilities as they consist of soft tissue with muscles running in different directions. This means that in addition to being independent of a skeletal structure, during motion of the lips and tongue, compression in one plane will result in expansion in another (Stone & Murano, 2007).

Though speech production is a complex process, the literature indicates the coordination of motor units or muscles for a complex motor task is achieved through the formation of functional synergies that act to reduce the potential degrees of freedom of movement (Latash, Levin, Scholz, & Schöner, 2010). Functional synergies have been defined as fundamental units of control organised to achieve functional goals that "… consist of collectives of muscles or motor neurons that in turn control muscle contractions" (Smith, 2010, p. 275). Thus synergies are regarded as a way of organising the speech system to reduce the potential degrees of freedom of movement, and give rise to preferred movement patterns. They are also considered dynamic in the sense that they are open to modification through changes in the central nervous system, specific task requirements and changes associated with motor learning and development. As such, synergies are expected to emerge, disappear and change.

The speech science literature provides data that support the existence of hierarchical sequences in speech motor control (specifically mandibular and labial coordination) that unfold over an extended developmental period. Individual articulators exhibit non-uniform developmental time paths that are differentiated by changes in the composition of inter-articulator relationships (Cheng, Mudoch, Goozée, & Scott, 2007; Smith & Zelaznik, 2004; Terband, Maassen, van Lieshout, & Nijland, 2010).

The development of early motor speech control

Within the hierarchy of motor-speech development, the mandible has been identified as foundational to the development and integration of more complex movements of the lips and tongue. For example, Green, Moore and Reilly (2002) found the mandible is the predominant contributor in early development, with engagement of the lips independent from the mandible increasing with age. That is, initially lip movements occur as a result of excessive mandibular displacement in the open phase creating excessive lip compression upon completion of mandibular closure. With development, differentiation between the mandible and lips is observed through decreased jaw displacement and increased upper lip and lower lip movements (Green, Moore, Higashikawa, & Steeve, 2000; Green, Moore, & Reilly, 2002; Walsh, Smith, & Weber-Fox, 2006).

In addition to the developmental trends observed in labial-mandibular coupling, there is also evidence to suggest the presence of developmental differences in muscle activation patterns of the mandible (Ruark & Moore, 1997; Steeve & Moore, 2009; Steeve, Moore, Green, Reilly, & McMurtrey, 2008). In a recent longitudinal electromyographic (EMG) study, Steeve and Moore (2009) examined the developmental differences in the coordinative muscles of the mandible in speech and non-speech tasks, in a typically developing single male infant from 8 to 22 months. They found organisational differences in muscle group activation for babble and true words across the developmental ages of their study. For example, during vowel babble there was increased EMG activity in synergistic muscle groups whilst greater coupling of the antagonistic muscle groups was observed in multi-syllabic vocalisations. These findings are in support of earlier work by Ruark and Moore (1997).

Smith and Zelaznik (2004) further examined the development of inter-articulator relationships by investigating two speech synergies – the mandible/lower lip and the lip (upper lip - lower lip) aperture synergies. Their data indicate the lower lip/mandible synergy is earlier developing than the lip aperture (upper lip - lower lip) synergy. Finally, whilst the tongue/jaw synergy has been less researched there is emerging literature that suggests tongue movements become increasingly disassociated from the mandible with increasing developmental age (Cheng, et al., 2007; Terband, et al., 2010).

In summary, early developmental changes in individual articulators and composition of functional synergies occur due to extensive changes in neuromotor pathways associated with maturation, anatomical/biomechanical composition, experience and practice.

The role of somatosensory input in speech production

Whilst the importance of sensorimotor feedback in speech motor-coordination is widely accepted, its role in altering speech-motor control is an area of current research focus. Specifically, perturbation studies have been used to explore the potential role of the somatosensory system to affect change in the coordination of movement synergies (Ito & Ostry, 2010; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Ménard, Perrier, Aubin, Savariaux, & Thibeault, 2008). These studies have shown that articulator coupling patterns will reorganise or compensate as a response to modification/disruptions in articulator movements (such as insertion of a plastic tube in the mouth or a bite block between the teeth), to maintain perceptual integrity and acoustic output. For example, Kelso et al. (1984) report on three experiments designed to examine the effects on articulatory cooperation between the jaw, lips and tongue, when a constant force load was applied to the jaw in both opening and closing gestures. They reported that whilst no perceived distortion to the speech signal was observed (acoustic analysis was not provided), kinematic and EMG analysis demonstrated compensatory changes. For example, when an unexpected force was applied to the jaw during production of the word /bæb/, compensation was observed through increased activity in the upper and lower lip. Similarly, during production of the word /bæz/ increased tongue activity (but not lip) was observed. They reasoned the lower-lip perturbations, particularly evident when the load was applied in jaw closing, occurred as a result of passive mechanical compensations; whilst a more active neuromuscular response in “locally linked articulators”, was indicated by increased EMG activity in the jaw opening experiments.

These perturbation studies suggest the potential to improve speech intelligibility through modifying speech movement patterns. Mefferd and Green (2010) explored the strength of the relationship between tongue kinematics and acoustic changes in the vowel /ia/ by manipulating speaking rate and loudness in 10 typical adult speakers during the production of a sentence. They found changes in tongue displacement were closely correlated with changes in acoustic vowel distance, and suggested the potential for speech intelligibility to be improved through maximisation of articulatory specification.

Speech subsystems in children with cerebral palsy

Impairment to the speech subsystems in children with CP has been reported in the literature (Pennington, Smallman, & Farrier, 2006), however empirical data detailing motor-speech movement patterns are limited. Kent and Netsell (1978) reported excessive mandibular displacement with lip and tongue blade movements highly dependent on the mandible in four children with athetoid CP. More recently Ortega et al. (2008) reported significantly decreased mouth opening and increased lateral deviation in children with spastic CP when compared with typically developing peers.

Most recently, a kinematic study by Hong et al. (2011) evaluated labiomandibular coupling in mono-syllabic and poly-syllabic speech tasks in twelve Mandarin-speaking children with spastic CP. They reported a significant difference in the temporal coupling between the lower lip and jaw movements using a cross-correlation analysis, for children with CP, as compared to the age matched peers. In addition, increased jaw open distance was also reported. These results support the findings of Kent and Netsell (1978).

Two possible explanations for impaired motor control in individuals with CP have been postulated: 1. aberrant activation of muscle synergies (Neilson & O'Dwyer, 1981) and/or 2. a poor relationship between the motor command and the resulting perceptual consequences of the movement (Kent & Netsell, 1978).

Whilst the literature reports on the successful use of modifications to breath support, speech rate and intensity in children with CP, limited research has evaluated the benefit of improving the timing and coordination of orofacial movements during speech to improve speech intelligibility (Pennington et al., 2006, Pennington et al., 2009; Fox, 2002).

One intervention approach that has been developed specifically to facilitate articulatory control for improved speech production; and has been indicated in the literature to be of "specific relevance to the remediation of dysarthria of childhood for children" is PROMPT (Murdoch & Horton, 1998, p. 401).

PROMPT Intervention

PROMPT (Prompts for Restructuring Oral Muscular Phonetic Targets) is an intervention approach that was developed for the management of speech production impairments. Hayden (2006) states that since initial conception, PROMPT has evolved to embrace a number of theorists that are aligned with dynamic systems theory. That is, the philosophy and conceptual framework of PROMPT acknowledges the influence of the interdependent relationships between the cognitive-linguistic, social-emotional and physical-sensory domains and the environment, on communication. Speech motor development specifically is viewed as consisting of co-dependent subsystems, with skill acquisition subject to the bidirectional interaction between existing and developing systems. Thus, motor learning is characterised by an alteration to the movement synergies unique to each individual (Doyon & Benali, 2005; Kostrubiec, Tallet, & Zanone, 2006).

Within PROMPT, the motor speech system (respiration, phonation, articulation, prosody) is assessed and interpreted using the Motor Speech Hierarchy (MSH). The MSH reflects the inter-hierarchical development of speech subsystem control.

The PROMPT approach uses tactile-kinaesthetic-proprioceptive input *during speech* to train appropriate degrees of freedom of movement (for example, limit or increase) for the integration of jaw, lip and tongue movements. It is hypothesised that the tactile-kinaesthetic input will facilitate modifications to the orofacial movements of speech (i.e., improvements in timing and coordination as measured through changes in distance, velocity and duration) and contribute to improvements in speech intelligibility.

This present study aims to make a contribution to the existing literature by reporting on kinematic changes to jaw and lip control using three dimensional (3D) motion analysis, and associated changes to speech intelligibility, in six participants with cerebral palsy (CP) subsequent to participation in a motor-speech intervention. The intervention consisted of two phases, with one level of the MSH targeted in the first intervention phase and one level higher targeted in the second intervention phase.

The data reported here forms part of a longitudinal study aimed at evaluating the effectiveness of PROMPT in children with CP. As PROMPT is a treatment approach that purports to make changes to motor-speech movement patterns, kinematic analysis was used to evaluate pre-existing and subsequent changes to motor-speech movement patterns. The analysis was not used to assess or set intervention priorities.

Two questions are addressed in this paper:

1. Do children with CP with moderate-to-severe speech impairment show changes in duration, velocity and distance measures of the jaw and lips subsequent to PROMPT intervention?

The following outcomes were hypothesised:

a. Participants will record the greatest magnitude of change to the kinematic measures that reflect the intervention priority being trained in the first intervention phase. For example, most participants commenced intervention at the mandibular level of control as measured on the PROMPT MSH. Thus, it was expected the measures of jaw control (e.g., jaw midline control, jaw path distance travelled and jaw opening distance) would show the greatest magnitude of change, with a trend direction towards typically developing peers.

b. Due to the biomechanical linkages between the jaw and lips, changes to the second intervention priority would also be observed during the training of the first intervention priority (phase B) but that during the training of the second intervention priority (phase C), a greater treatment effect would be observed. That is, participants that received intervention focused on labial-facial control would show changes to the labial-facial measures (e.g., lip rounding) during the second intervention phase.

c. The training of new motor-speech movement patterns would result in destabilisation of an existing pattern of motor-speech movement patterns. As a result, with the initiation of a new motor-speech movement pattern, an initial “worsening” of the targeted behaviour may be apparent until speech subsystem re-organisation is achieved. Continued skill acquisition during the follow-up non-intervention period would be expected with stabilisation of the newly acquired motor-speech-movement patterns.

d. Control targets (for example, the production of words that require lingual control and which were not targeted in intervention) will not show a treatment effect.

2. Do children with CP with moderate-to-severe speech impairment show improvements in speech intelligibility subsequent to the PROMPT intervention?

It was hypothesised that improvement in speech intelligibility would be cumulative across the study phases.

Method

Participants

Six participants with CP (3 males, 3 females, age range 3 – 11 years), recruited through The Centre for Cerebral Palsy (TCCP), participated in the study (Table 1). Inclusion criteria were: diagnosis of CP, aged between 3 and 14 years, a standard score ≥1. 5 standard deviation (SD) below the mean on the Arizona Proficiency Scale – 3rd Revision (Arizona-3) (Fudala, 2001) and a developmental quotient ≥70 as measured on the Leiter-Brief International Performance Scale R Brief (Leiter-R) (Roid & Miller, 1997). Exclusion criteria were: receptive language impairment >2SDs below the mean on the CELF-P (Wiig, Secord, & Semel, 1992) or CELF 4 (Semel, Wiig, & Secord, 1995), a hearing impairment >25dB hearing loss, the absence of motor speech impairment (i.e., within age appropriate limits on The Verbal Motor Production Assessment for Children (VMPAC) (Hayden & Square, 1999), non-correctable visual impairment, and past exposure to PROMPT intervention.

Twelve typically developing (TD) peers were recruited to serve as a reference group for interpretation of the kinematic data. Table 1 illustrates the number and mean age of the TD peers age-and-sex- matched to each participant. Throughout the paper the terms “TD peers” and “participants” will be used to refer to the age-and-sex-matched TD peers and participants with CP, respectively. All TD peers scored within age-appropriate limits on oral motor and speech tests [The Arizona Proficiency Scale (3) (Fudala 2001) and The Verbal Motor Production Assessment for Children (VMPAC) (Hayden & Square, 1999)]. Family report indicated no history of speech/language impairment. All participants and the TD peers passed a pure-tone hearing screening at 20dB at 1000, 2000, 4000 and 8000Hz. English was the first and primary language of all participants.

Procedure

This study was approved by the Human Research Ethics Committees of LaTrobe University, Princess Margaret Hospital, and Curtin University. Parents provided informed written consent for their children to participate.

The kinematic and speech intelligibility data reported in this paper were collected to investigate trends and changes in motor-speech-movement behaviours, as part of a longitudinal single-subject ABCA multiple-baseline-across-participants-and-behaviours research design.

Experimental control was maintained through the establishment of a stable baseline for all participants prior to the commencement of intervention; and the repeated measurements of both targeted and control behaviours, *throughout* the study phases. This involved the weekly administration of speech probes for each baseline session (A1), at the end of each treatment session (phases B and C) and at 12-weeks post-intervention (phase A2). The speech probes consisted of three groups of twenty words. Group one contained trained and untrained words based on intervention priority one, group two contained trained and untrained words based on intervention priority two and group three contained control words based on the untrained intervention priority three.

The study phases were as follows:

Phase A1: The baseline data collection phase consisted of a 5- to 8-week period during which time participants received their standard therapy services. This consisted of regular physiotherapy and occupational therapy sessions.

All participants remained in baseline until stable baseline measurements were determined through the application of statistical process control (Portney & Watkins, 2009). Two participants were in baseline for 5-weeks, 1 for six-weeks, 2 for 7-weeks and one for 8-weeks.

Phase B: PROMPT intervention aimed at one level of the PROMPT motor speech hierarchy (MSH).

Phase C. PROMPT intervention aimed at one level higher on the MSH.

These two phases each consisted of 10x once weekly individual intervention blocks, 45 minutes in length. Therapy sessions occurred at the same time of day on the same day of the week.

Phase A2: Follow-up data collection. This consisted of two data collection sessions. Session one comprised the collection of the kinematic and speech intelligibility data. The speech probe data were collected in the second session. Following this study phase, all participants returned to their regular therapy services, consistent with the baseline phase.

The kinematic and speech intelligibility data reported in this paper were collected *at the end* of each study phase. Portney and Watkins (2009) suggest the inclusion of multiple pre/post measurements can offer valuable information regarding trends over time, particularly when internal threats to validity (such as the inclusion of these measures in association with the speech probe measures) can be controlled.

Four PROMPT trained therapists administered the intervention protocols. Inclusion criteria for therapist participation in the study included (a) completion of the Introduction to Technique workshop, (b) completion of the case study detailed in the Introduction to Technique manual within 3 months of the workshop, (c) regular use of the technique for at least 9 months, (d) attendance at a PROMPT mentoring day held by Deborah Hayden in October 2006, (e) a fidelity rating to the PROMPT approach of no less than 80% as assessed by an independent senior PROMPT Instructor, and (f) an expression of interest to participate in the study.

The therapists only administered the PROMPT intervention. They were not involved in any scoring or administration of testing protocols.

Measures

Kinematic data.

Five repetitions of 11 untrained stimulus words were used to elicit the kinematic measures of distance, velocity and duration.

Three distance measures of the jaw were calculated:

1. Jaw path distance travelled (JPD) - Sum of the 3D Euclidian distance of the jaw marker across each time sample.
2. Jaw open distance (JOD) - The 3D Euclidian distance between the forehead marker and jaw marker subtracted from the corresponding distance at rest.
3. Midline control (MC) - Average lateral displacement of the middle lower lip + jaw marker (LL) from rest .

Mean maximum movement measures were obtained for JOD, whilst the JPD and MC measures were based on the average value obtained across the repetitions.

These three distance measures reflect the components of level III (mandibular control) of the MSH and were used to assess mandibular control pre and post intervention.

Two distance measures of the lips were extracted and calculated:

1. Lip Rounding/Retraction (LR/R): Distance between the left and right corners of the lips in the horizontal plane boundary. As this measure is subtracted from rest, a positive value indicates retraction and a negative value indicates rounding.
2. Inter-lip distance during bilabial contact (BLC), obtained on the 4 stimulus words containing the bilabial (m, p, b) in word initial position, consists of two components:

   a. Minimum inter-lip distance during bilabial contact: calculated as the 2D Euclidian distance between the upper lip (located at midline on the vermillion border of the upper lip) and the lower lip (located at midline on the vermillion border of the lower lip), based on the movement boundary.

b. Position of the upper lip (UL) and lower lip (LL) at the point of minimum bilabial contact calculated in the vertical position.

These distance measures were extracted to reflect the components of level IV (labial facial control) of the MSH and were used to assess labial-facial control pre and post intervention.

Peak velocity and average duration measures were calculated on the LL marker, thus representing the combined action of the jaw and lower lip.

The kinematic stimulus words, illustrated in figure 2, spanned three levels of the PROMPT MSH and the articulatory vowel space:

1. Word-set one (Mandibular Control): *mine*, *man*, *hat*, *up*.

This word-set contains low vowels that are consistent with PROMPT jaw height positions three and four.

2. Word-set two (Labial-facial Control): *push*, *beep*, *two*, *shop*, *off*[1].

This word-set contains high vowels that are consistent with PROMPT jaw height positions one and two.

3. Word-set three (Lingual Control): *six*, *spot*.

This word-set contains words that are consistent with stage V of the PROMPT MSH. These words were included to assess whether the added complexity of the lingual control was reflected in the jaw and lip measurements.

The kinematic stimulus words were untrained and designed to reflect changes in jaw and lip movements. Due to the severity of the speech impairment in the six participants, the

[1] In a young child the jaw height position will be lower and produced within the mandibular plane. In a mature system the jaw height position will be higher and produced in the labial-facial plane.

untrained stimulus words were presented in isolation and not embedded in carrier phrases. They were presented in random order for each participant to repeat.

Instrumentation.

Jaw and lip measurements were tracked in three dimensions (3D) at a sampling rate of 50 frames/sec using Vicon Motus (9. 1). Data were captured in standard PAL DV format (720 x 576 pixels) using three Sony HDR-HC3E PAL HDV 1080i video cameras mounted on Sony remote control tripods (VCT-D68ORM). The speech acoustic signal, recorded at 44 kHz, was simultaneously recorded using a wireless Bluetooth microphone (Sony ECM-HW 1R) connected to the central video camera.

The position of each facial marker was calibrated to a 24 cm x 24 cm reference cube containing 8 spherical markers. The circular facial markers of interest, for the measurements reported in this paper, include:

1. A reference array used to create the three dimensional (3D) head-based coordinate system, independent of head rotation and translation.

This contained four forehead calibration markers and one nose marker. The x, y and z axis represented the horizontal, vertical and orthogonal axes, respectively.

2. Markers used to define the movements under investigation.

One jaw marker was placed at the base of the mental protuberance of the chin. Eight lip markers were placed as follows: 1. Right and left corners of mouth, 2. Right and left upper points of Cupid's bow, 3. Midpoint located on the lower lip (LL) vermillion, and 4. A virtual marker located on the upper lip (UL) vermillion. The LL marker represented the combined motion of the lower lip and jaw.

Vicon Motus is designed to track movements automatically by detecting a contrast between a circular or spherical marker and the surrounding pixels. A light source adjacent to each camera and retro-reflective markers positioned on the moving person are usually used to create this contrast (bright white against a darker surround). During piloting for this study, the facial movements during speech production placed the participants at potential risk of swallowing some of the spherical retro-reflective markers. Therefore, in this study, black liquid eyeliner and white zinc lipstick were used to create flat circular markers (2. 5mm in diameter) against a contrasting background (i. e. black markers against a lighter surround).

Data processing.

Following digitisation, the isolated data (independent of head rotation and translation) containing the word as measured within the onset and offset boundaries, were smoothed and time normalised to 200 points using a cubic spline algorithm (De Boor, 2001).

The start and endpoint of each word was initially identified visually using the plotted waveform viewed in one of the custom written LabVIEW programs. The audio files were then exported into a spectrographic analysis program (SFS/WASP, Huckvale, 2003) with word boundary onset and offset identified as the onset and cessation of the acoustic energy associated with each word. The word onset for the measure of bilabial lip contact was calculated as the first zero crossing of the LL velocity/time waveform before the acoustic onset.

Each distance measure was normalised to a mean rest position for each participant, on each testing occasion. This cancelled out the effect of changes in the resting face shape and possible small variations in marker placement across the phases of the study (Faraway, 2004).

Three custom programs, written using LabVIEW 8.6.1 (National Instruments Corporation, Austin, TX, USA), were used to extract the data. Data analysis was based on the whole word.

Reliability measures for the kinematic measures of distance, velocity and duration were not undertaken as the data are extracted automatically using custom written programs.

Speech intelligibility.

Speech intelligibility was measured at a single word level using the Children's Speech Intelligibility Measure (CSIM) (Wilcox & Morris, 1999). This is a standardised test that consists of a word-list of 50 words. A listener is required to select the word they have heard from a multiple-choice selection. The test contains 100 different versions of the stimulus list. This allows the investigator to randomly select from a number of word lists to prevent practice effects. The authors report same form test-retest reliability correlation coefficients between .79 and .91; and alternate form correlation coefficients between .64 and .86. Correlations were weakest for the younger age-groups. Previous research evaluating treatment effectiveness in children with CP, has found this test to be sensitive to change in a similar time frame to this study (Pennington, et al., 2006).

The CSIM was administered by the first author. An independent untrained naïve listener scored all the score forms for each of the participants on each testing occasion. The listener was blinded to the participants, testing occasion and purpose of the study. The scoring was completed in blocks with a two-to three month time frame between scoring occasions. Each participant completed a different stimulus list on each testing occasion.

Reliability of speech intelligibility was obtained by randomly allocating 20% of the de-identified data to the untrained naive listener to re-score. Intra-rater reliability of 100% was obtained.

Intervention

Participants attended therapy once a week for a duration of 45 minutes. Intervention protocols were individually tailored to reflect the individual interests and age of each participant using a consistent procedure for all individuals and administered in accordance with the tenets of the PROMPT philosophy as outlined in the PROMPT Bridging manual (Hayden, 1995b). Each treatment session followed the same format. The session commenced with a 5 minute warm-up period, followed by a 15 minute activity. Upon completion of the activity a second 5 minute warm-up was followed by a second 15-minute activity. The warm-up period consisted of massed practice of individual phonemes and words. All participants were encouraged to start in a neutral posture (i.e. lips softly closed together without excessive retraction). Knowledge of performance feedback was provided after each trial. During the 15 minute activity words from the trained word-set pool were practiced in a distributed manner. Knowledge of performance and results were randomly given. No prescribed schedule was adhered to and varied across the therapy sessions. However, therapists were required to provide information regarding the motor movement pattern and perceptual accuracy. For example, “you opened your mouth too wide, let’s do that again with a smaller mouth”. The PROMPT technique was applied as described in the Introduction to Technique Manual (Hayden, 1995a).

The PROMPT System Analysis Observation and Motor Speech Hierarchy (Hayden, 1995a) were used to analyse the participant’s motor speech control and set intervention objectives, using data from the speech and language measures administered for participant inclusion. Three intervention priorities were selected and treatment objectives written for the first two. Participant 1 targeted labial-facial control in phase B and lingual control in phase C. Participants 2, 3, 5 and 6 targeted mandibular control in phase B and labial-facial control in phase C. Participant 4 targeted mandibular and labial-facial control simultaneously in phase B and lingual control in phase C. Each participant’s intervention priorities across the intervention phases are illustrated in table 2.

Fidelity

Fidelity to the intervention was evaluated by a PROMPT Instructor who was blinded to the phases of the study and intervention sessions. Video recordings of the intervention sessions were randomly selected by a research assistant, de-identified and sent to a senior PROMPT Instructor to rate using the PROMPT fidelity measure reported by Rogers et al. (2006). Prior to commencing the study, each therapist's fidelity to the PROMPT approach was evaluated, with all therapists obtaining a minimum of 80%. Fidelity measures throughout intervention block one (phase B) ranged between 77.7% and 93%. All therapists achieved fidelity ratings during intervention block two (phase C) ranging between 80.2% and 97%. Therapists were not given feedback on their fidelity ratings throughout the study phases.

Statistical Analysis

Non-parametric and descriptive statistics (means and standard deviations) were used to analyse the kinematic data on each measure of distance, velocity and duration within each word-set. The Mann-Whitney test was used to determine the significance of the differences between the participants to the TD peers at pre-intervention. Friedman's ANOVA ($p \leq .05$) was used to test whether the PROMPT intervention had a significant effect on each of the measures of distance, velocity and duration for each of the word-sets post intervention. Bonferroni-corrected pairwise comparisons using the Wilcoxon signed-rank test ($p \leq . 01$) were used to evaluate differences to each of the measures, for each of the word-sets, across the study phases. Two-tailed tests were used on all mandibular, velocity and duration measures. One-tailed tests were used on LRR and BLC based on a priori knowledge that all participants had pre-intervention values that exceeded the TD peers; and intervention was aimed at reducing the distance.

In addition, the magnitude of the treatment effect was evaluated using effect size data calculated on each individual word across each of the intervention phases. Effect sizes were calculated using the Wilcoxon signed-rank test and interpreted as moderate at .3 and large at .5 (Field, 2009).

Results

Kinematic Data

The results will be presented for each measure in turn. First, a summary statement followed by the data for each measure will be presented. Comparison to the TD peers *prior* to intervention will be presented, followed by the results for each measure *post* intervention. A summary of the effect size data concludes the reporting of the kinematic data.

The data show all participants recorded changes to the kinematic measures across the study phases.

Distance.

Jaw open distance (JOD).

Pre-intervention: Statistically significant differences were recorded on the measure of JOD for all participants as compared with the TD peers (see table 3).

The descriptive data for word-set one (containing low vowels including /æ/ and /ʌ/), show P2, P4, P5 and P6 recorded reduced values, P1 recorded values that were within range, and P3 recorded values that exceeded the age-and-sex-matched TD peers. The descriptive data for word-set two, (containing high vowels including /i/ and /u/), show five participants (P1, P2, P3, P5, P6) recorded values that exceeded those of their peers, whilst one participant (P4) recorded reduced values.

Post-intervention: Statistically significant changes in JOD values and a trend towards the TD peers were observed for all participants subsequent to PROMPT intervention (see table 4).

A cumulative treatment effect across the study phases was observed. Results on the pairwise comparisons show P3 and P4 recorded changes in mean values that reached statistical significance between both phases A-B and B-C. P3 initially recorded increased mean values on word-set one between phase A-B (during this phase JPD and lateral deviation from midline values decreased), whilst phase C recorded decreased values and a trend towards the TD peers. P1 (word-set two), P2 and P6 recorded trend directions towards their peers but did not record changes in values that reached statistical significance until phase B-C. The descriptive data show P6 recorded a decrease in the mean JOD values on word-set one between phases B-C. This occurred when intervention targeted a decrease in values on word-set two. The change in values for P1 reached statistical significance during the consolidation phase between phase C and D.

Jaw path distance (JPD).

Pre-intervention:

Five participants (P1, P3, P4, P5, and P6) recorded significantly different values to the TD peers on the measure of JPD.

Post-intervention: Four participants (P1, P4, P5, and P6) recorded statistically significant differences in JPD values subsequent to the PROMPT intervention and a trend towards the TD peers (see table 5).

The pairwise comparisons show statistically different values were recorded for P4 on word-set one at the end of phase B. At the end of phase C significantly different values were recorded in word-set one by P1, P3 and P6.

Midline control (MC).

Pre-intervention: Five participants (P1, P2, P4, P5 and P6) recorded values that were significantly greater in comparison to their age-and-sex-matched TD peers (see table 3).

Whilst P3 recorded increased lateral deviation from midline on three individual words in word-set one (on the words that recorded the largest JOD values) the word-set did not reach statistical significance.

Post-intervention: Participants P1, P2 and P6 recorded changes to values on the measure of MC that were statistically significant subsequent to intervention (see table 6).

The pairwise comparisons show significant changes were recorded for P1 on word-set two at the end of phase C. The descriptive data show this participant recorded increased lateral deviation from midline in this phase. This was associated with increased retraction during anterior tongue elevation for lingual sounds. P3 and P6 recorded statistically significant changes to word-set two and one respectively, at the end of phase B. These participants showed a trend towards improved midline stability.

Lip rounding and retraction (LR/R).

Pre-intervention: All participants recorded mean values on words in each word set that significantly exceeded the values recorded by the age-and-sex-matched TD peers.

Three participants (P1, P2 and P3) recorded increased values on all word-sets, P5 and P6 word-sets one and two. P4 recorded increased values on 3/5 words in word-set one but significance for the whole word-set was not reached.

Post-intervention: All participants recorded a significant difference subsequent to the PROMPT intervention (see table 7). Five participants recorded changes that indicated a decrease in values and trend towards the age-and-sex-matched TD peers. P1[2] recorded increased values and a trend away from the age-and-sex-matched TD peers.

Pairwise comparisons show at the end of phase B, four participants recorded significantly different values in the LRR distance: Participants P3 (all three word-sets), P2 (word-set one) and P6 (word-set two) recorded significantly reduced values. P1 differed to all participants and recorded an increase in LRR distance.

[2] The data for P1 differs from the other participants. This participant received training at the labial-facial level of control in phase B and lingual level of control in phase C. More detailed analysis of this participant's data shows the trend away from the TD peers was associated with subsystem re-organisation as P1 made modifications to achieve intra-oral tongue separation for the production of lingual sounds.

At the end of phase C, 5 participants recorded statistically significant changes in at least one word-set. Four participants recorded reduced values, whilst P1 continued to record increased values. However, between phase C and D this participant (P1) recorded significantly decreased values, with most values recorded lower than at pre-intervention.

Inter-lip distance during bilabial contact (BLC).

Pre-intervention: Five participants recorded values that differed from their peer**s** (see table 8). Four participants (P1, P2, P4 and P5) recorded inter-lip distances that were greater and one participant (P3) less than those recorded by the age-and-sex-matched TD peers. All participants recorded positive UL and LL values. This indicates both lips were positioned superiorly to the rest position at the point of minimum bilabial contact. These results differ from the TD peers where values inferior to the rest position were recorded in the UL. The LL position was on average 1mm superior to the rest position, thus indicating only a slightly elevated position at the point of minimum bilabial lip distance.

Post-intervention: One participant (P1) recorded significantly different BLC values on all four words subsequent to the PROMPT intervention. The pair-wise comparisons show the change in values reached statistical significant between phases A-D (see table 9).

Whilst P1 was the only participant to record a significant change in BLC, a further four participants recorded significant changes in the interaction between the UL and LL during minimum bilabial contact. A decrease in LL and UL values indicated a decrease in the superior elevation of the LL. All participants also recorded negative values in the UL, however, the change to these values were not statistically significant.

P1, P2 and P3 recorded statistically significant changes to the LL position subsequent to intervention. Pairwise comparisons show P3 recorded statistically significant changes across all phases of the study (figure 3 illustrates an example of the change in UL and LL position in one word for P3 across the study phases), P2 between phase B-C and P1 between phases A-D (see tables A1 and A2).

Velocity.

Pre-intervention: Whilst all participants recorded statistically significant values on the measure of peak velocity for individual words, only one participant (P3) recorded statistically significant different values on all three word-sets. Three participants (P1, P5 and P6) recorded significantly different values on word-set two.

Post-intervention: Two participants (P4 and P6) recorded statistically significant changes to peak velocity values in complete word-sets subsequent to intervention (see table 10). These participants recorded values that indicated a trend towards the values generated by the age-and-sex-matched TD peers. Pairwise comparisons show phase B yielded significant change for both participants. Participant 6 continued to record significant changes between phases B-C.

All other participants recorded significant changes to specific words, only.

Duration.

Pre-intervention: Average duration was longer for four participants (P1, P3, P5 and P6) on all three word-sets and two participants (P2 and P4) recorded significantly longer durations on word-set three only, when compared with the TD peers.

Post-intervention: All participants recorded significant changes to the measure of duration (see table 11). Pairwise comparisons indicate a statistically significant change in values for P6 and P3 recorded between phase A-B and phase B-C, respectively. Three participants recorded significantly different values in the follow-up phase (C-D).

Inter-relationship between the measurements of distance and velocity.

The measurements of maximum jaw open distance and peak velocity were observed to be related. Usually, an increase in displacement will result in a co-occurring increase in velocity and vice versa. For four of the five participants that recorded significant changes in velocity this relationship was observed. One participant (P4) also demonstrated this trend during the intervention (phases B and C) but recorded a decrease in velocity with increased JOD at follow-up (phase D).

Effect size data.

The effect size data indicate the greatest magnitude of change between phases A-B was recorded on the measure of JOD on word-set one for participants P2, P3, P4, P5 and P6. Moderate-to-large effect sizes (.38-.64) were recorded on at least 65% of the words contained in this word-set for these five participants. Words contained within word-sets two and word-set three also showed treatment effects at the end of phase B, however, the percentage of words recording large effect sizes was substantially less (19% and 20%, respectively).

Between phases B-C, the greatest magnitude of change was recorded on the measure of LRR for participants P1, P2, P4, P5 and P6. Both word-sets one and two recorded moderate-to-large treatment effects.

Speech Intelligibility

Intelligibility scores for each participant are shown in table 12. The test score and confidence intervals are reported as scored by an independent, untrained naive listener.

All participants recorded improved speech intelligibility, with five participants recording an increase in speech intelligibility greater than 14% at the end of the first intervention (phase B). Continued improvement was observed for 5 participants at the end of the second intervention (phase C).

Non-overlapping confidence intervals indicate 5/6 participants demonstrated a significant difference in speech intelligibility between the pre-intervention and follow-up phases. Three participants continued to make gains post-intervention. All participants maintained speech intelligibility scores at 6 -8 weeks post-intervention that exceeded pre-intervention scores.

Effect size data show the greatest magnitude of change occurred between phases A-B (.79), with a small incremental increase phase B-C (.3). An effect size of 1.1 was recorded post intervention (phase A-D).

Discussion

In this paper, changes to the measures of distance, velocity and duration, of the jaw and lips of children with CP, subsequent to PROMPT intervention, were evaluated. The kinematic measures of the participants were also compared to a small group of TD peers. This was for the purposes of interpreting the functional movement synergies in the participants with CP compared to those exhibited by their TD peers *prior* to intervention and the trend direction of the changes *subsequent* to PROMPT intervention.

The pre-intervention findings of the speech movement patterns were characterised by the use of movement patterns that indicated functional impairment to jaw control. Participants with a diagnosis of hemiplegia (P2, P4, P5 and P6) demonstrated the most comparable movement patterns whilst participants 1 (dyskinesia) and 3 (spastic quadriparesis) the most dissimilar. Low levels of speech intelligibility accompanied these movement patterns in all participants.

Post-intervention data indicate all participants recorded significant changes in the jaw and lip measures that reflected those targeted across the phases of the study. Improved speech intelligibility accompanied these changes for all participants.

The study results are discussed first by assessing the pre-existing motor-speech patterns then followed by discussing the changes observed subsequent to intervention. The use of PROMPT and specifically tactile-kinaesthetic input in the establishment of new motor-speech-movement patterns is subsequently evaluated.

Pre-existing Motor-Speech Movement Patterns

All participants recorded jaw distance values that indicated reduced jaw movement space and grading (see animation 1). That is, four of the six participants (P2, P4, P5 and P6) recorded reduced jaw movements in words containing low vowels, and five participants (P1, P2, P3, P5 and P6) exhibited increased movements in words containing high vowels. Four participants also recorded measures that showed increased lateral deviation from midline, thus indicating jaw instability.

The jaw movement patterns of P3 differed markedly from the other participants. In contrast to the other participants all jaw movements were excessive across all words. Thus, there was limited difference between the mean values between words containing high and low vowels. These results are consistent with the interpretation of poor jaw grading and reduced movement space.

The use of reduced jaw movement space could be interpreted as either a compensation strategy aimed at achieving jaw stability or a function of the neurological damage associated with CP. The literature indicates increased precision in movement can be achieved through limiting the degrees of freedom of movement through voluntary increases in stiffness (displacement against resistance) (Nazari, Perrier, Chabanas, & Payan, 2011). Shiller, Laboissiére and Ostry (2002) found jaw positions that were closer to occlusion (e.g., high vowels) recorded increased stiffness whilst jaw movements associated with low vowels recorded lower levels of stiffness. Given the jaw provides postural support for the lips and tongue, the use of reduced jaw space observed in the participants in this study could be viewed as an adaptive strategy in an attempt to increase stability and precision of movement. Support for this hypothesis can be found in CP gait and upper limb literature (van Roon, Steenbergen, & Meulenbroek, 2005).

Alternatively, the reduced movement space could be considered a function of aberrant motor control, as a result of impairment in the central nervous system. Increased stiffness may be achieved through co-activation of agonist and antagonist muscles and is a feature of early motor learning (Darainy & Ostry, 2008). However, the literature reports evidence of excessive co-contraction in children with CP, as compared with TD peers (Tedroff, Knutson, & Soderberg, 2008). Neilson and O'Dwyer (1981) also proposed the abnormal timing and sequence of muscle activity observed in their adult dysarthric speakers may be due to inappropriate contractions of antagonistic muscles reducing the effectiveness of agonist muscles. Thus, both interpretations for explaining the reduced movement space are plausible and suggest the need for further research.

In addition to reduced movement space, five participants demonstrated impaired interaction between the upper lip (UL) and lower lip (LL) during bilabial closure. The vertical position of the UL and LL at minimum bilabial contact, as measured in the kinematic signal, was used to evaluate the interaction between the UL and LL in this study (Löfquist & Gracco, 1997). Five participants demonstrated significantly different inter-lip distance measures on at least 2/4 words. Three participants (P3, P4 and P6) recorded excessive elevation of the LL in comparison to the age-and-sex-matched TD peers, with P3 recording values that indicated the LL exceeded the UL during bilabial closure. All participants recorded values that indicated limited engagement of the UL. The age-and-sex matched peers in this study recorded mean negative values between -1and-5mm. This value indicates that at the point of minimum bilabial contact the UL was positioned inferiorly to rest. The participants with CP however, recorded positive values that indicated an elevated UL position. Empirical research has shown that whilst considerable variability exists in individual movement patterns, the UL displacement is influenced by the position of the LL (Green, et al., 2002; Löfqvist & Gracco, 1997). The results obtained here suggest either the

LL forced the UL superiorly or that lack of bilabial contact resulted in an absence of compression. These results indicate the jaw was the principle articulator driving bilabial closure.

In addition to difficulty with bilabial lip contact, all participants used an excessive pattern of lip retraction across neutral, rounded and retracted phonemes in comparison to the TD peers (see animation 2). This may suggest difficulty grading lip movements or possible recruitment of additional muscles to maintain jaw opening and closing movements. The generation of compensatory labial movements to maintain jaw control (Folkins & Canty, 1986; Gomi, Honda, Ito, & Murano, 2002) lends support to this interpretation. The difficulties observed on two measures of lip retraction/rounding and bilabial closure suggest poor integration of lip and jaw movements.

Motor-speech movement patterns subsequent to PROMPT

The PROMPT intervention protocol was designed to acknowledge the inter-hierarchical relationship between existing and developing behaviours, and the stages of motor acquisition and consolidation. When intervention focuses on establishing a skill that is within an existing coordination synergy, both an increase in performance and stabilisation is expected. These newly established behaviours are vulnerable to competition. Consequently, when intervention focuses on developing a skill that requires re-organisation of existing co-ordination synergies, competition between the existing synergies may occur as a result of learning being biased to the “to-be-learned” behaviour. Consolidation defines the post-training phase where continued gains in performance may be observed and susceptibility to interference/competition decreases (Kelso & Zanone, 2002).

The results obtained in Phase B (intervention priority one) of this study are consistent with the expected early stages of motor learning. The data for all participants indicate a trend towards the performance patterns of their age-and-sex-matched TD peers on the targeted intervention priority that were accompanied by gains in speech intelligibility. In addition, the kinematic data were collected one week post-intervention, thus indicating the new functional synergy had been established and retained in that period.

The results obtained in phase C represent not only acquisition of a new functional synergy but also the impact of training this new behaviour on a recently acquired skill. All participants recorded a trend direction toward their age-and-sex-matched typically developing (TD) peers on the behaviour targeted during intervention priority two, accompanied by changes in speech intelligibility. Again, the testing was conducted one week-post intervention, similarly suggesting retention of the newly established behaviours. Whilst some participants continued to record improvement on the first intervention priority, three participants (P1, P3 and P5) recorded a trend away from the TD peers on some behaviours targeted in phase B. One participant (P5) also recorded an associated decrease in speech intelligibility. These results suggest a change in the dynamics of the newly established coordination patterns on the earlier trained intervention priorities (of phase B) as indicated by the results obtained on intervention in phase C.

A number of possible processes may be considered as explanation for the trend away from the TD peers in phase C for skills previously acquired in phase B. The work of Zanone, Kostrubiec and Temprado (2006) indicates the “empirical signature” of skill acquisition is the concurrent improvement of both accuracy and stability. An a priori decision was made to continue to the next intervention phase regardless of performance. Thus, the newly acquired motor pattern may not have been sufficiently established or stable and consequently vulnerable to interference. However, the work of Dorfberger, Adi-Japha and Karni (2007), indicated children are less susceptible than adolescents and adults, to interference. Given these findings, a second plausible explanation is that the introduction of the second intervention priority imposed adaptation by establishing “a new attractive state of the underlying coordination dynamics close to the task requirement" (Kelso and Zanone, 2002, p. 782). This adaptation may have been essential to the process of integration for the development of more functional movement synergies.

An additional explanation drawn from neurophysiological research considers the potential for a relationship to exist between the type of cerebral palsy (and severity) and potential impact on retention of motor speech learning. Recent brain imaging studies have indicated a time course of differential plastic changes in the neural system throughout the process of motor learning. Specifically, the research of Doyon and Benali (2005) indicates that whilst both the cortico-striatal and cortico-cerebellar systems both play a role in motor skill acquisition, the automatic execution of motor adaptation tasks produces long term plastic changes in the cortico-cerebellar system. One of the participants (P1), who recorded a decrease in earlier acquired behaviours between phase B and C, had a diagnosis of dyskinetic CP. This type of CP is characterised by impairment to the cerebellum and basal ganglia. This therefore raises the potential value of research into understanding the role of the cortico-cerebellar system in long-term retention of newly acquired motor skills in children with CP.

The data in this study suggest the potential need to consider the integration of consolidation periods into the design of intervention programs. Post intervention data (phase D) show all participants continued to record changes to the movement patterns of the jaw and lips. The data indicate a trend towards the age-and-sex-matched TD peers, including those measures that had moved away during phase C. Four participants also recorded follow-up measures that indicated continued improvement in speech intelligibility in the absence of intervention. These data suggest the non-intervention period that occurred at the end of phase C provided a period of consolidation that resolved the competition between the motor-speech behaviours that were targeted across the two intervention priorities. These results are supported by recent research that found prior to adolescence, continued improvement during the consolidation phase occurred (Dorfberger, Adi-Japha, & Karni, 2007). Delayed post testing is recommended as a tool to assess acquisition and generalisation in treatment (Maas et al., 2008). The value of considering time as a critical piece in the development of an intervention protocol aimed at establishing new motor speech movement patterns, for children with impaired motor speech control, is possibly indicated.

The use of PROMPT as an intervention approach for children with speech impairments associated with CP

The results of this study suggest the use of tactile-kinaesthetic input, applied systematically and actively during speech, contributed to modifying the speech-movement patterns of the participants and led to increased intelligibility. Whilst the importance of sensorimotor feedback for speech is widely accepted, more recent research highlights the task-specific role of sensorimotor adaptation in motor learning. Specifically, empirical data suggest proprioception can be modulated to provide greater acuity for limb positions when the information is paired with a functionally relevant and active motor task (Wong, Wilson, & Gribble, 2011).

Researchers have hypothesised that the differing patterns of muscle activity observed in individuals with cerebral palsy may be as a result of impaired sensory-motor feedback (Kent & Netsell, 1978; Neilson & O'Dwyer, 1981). Recent research using diffusion tensor imaging (DTI) studies support this by revealing children with CP show deficits in proprioception as a result of abnormalities in thalamocortical pathways (Hoon et al., 2009).

A PROMPT trained clinician uses specific tactile-kinaesthetic input *during active speech*. The tactile-kinaesthetic input is directed to specific orofacial regions that are richly innervated with slowly adapting, cutaneous mechanoreceptors that are responsive to external low level inputs during motor activity (Trulsson & Johansson, 2002). Thus it is plausible to consider that the proprioceptive input, coupled to specific movements in active speech, may have provided additional somato-sensory representation that facilitated change to the motor speech output (Kelso, Fink, DeLaplain, & Carson, 2001).

It is none-the-less recognised that PROMPT is but one intervention approach. Other interventions that do not provide tactile-kinaesthetic input have also reported changes to the displacement of the jaw, lips and tongue. For example, the Lee Silverman Voice Treatment (LSVT®) is also a treatment technique framed within the principles of DST. Whilst the focus of this treatment approach is increased loudness, changes to movements of the jaw, lips and tongue have been inferred from acoustic measures. Further research is required to understand the contribution of the tactile input into modifying the speech motor behaviours.

Limitations

The motion analysis system used to evaluate the kinematic measures in this system does not record lingual motion. Two participants commenced at the labial-facial level of control and moved to the lingual level of control as measured on the MSH. Direct measurement of changes to the targeted intervention priority (lingual control) was not possible. Thus, the phase C data reflected changes in mandibular and labial-facial control subsequent to intervention targeting lingual control. Further analysis using a system that records changes in jaw, lip and tongue measures would have allowed for clearer interpretation of the data for the participants that targeted lingual control.

The participants in this study had moderate-to-severe speech impairment. This prevented the stimulus words from being embedded in carrier phrases thus limiting some possible analyses. A repetition of this study using a smaller data set, and less severe speech impairment would allow the embedding of words in carrier phrases and would provide the opportunity to perform analyses that would make a contribution to further understanding motor speech control in children with CP.

Conclusion

The results reported in this paper suggest the PROMPT intervention was effective in supporting changes to the motor-speech patterns of children with cerebral palsy, that were associated with improvements in speech intelligibility across the therapy phases.

Prior to intervention, all participants presented with speech movement patterns that suggested impaired mandibular control, with reduced movement space. This has been reported in the literature in other motor speech impairments not associated with CP. Further research aimed at elucidating whether this is a compensatory strategy aimed at stability or a function of the motor impairment would be of benefit.

Post-intervention data indicate all participants recorded significant changes in the jaw and lip measures that reflected those targeted across the phases of the study. Whilst kinematic analysis was not used to establish intervention priorities, the continued improvement in some measures between phase C and D highlight the need for further research to not only evaluate performance and stability within intervention priorities, but also the timing between and across intervention priorities. This may make a contribution to further refining therapy protocols aimed at improving motor speech control.

Although our understanding of how the central nervous system uses sensory information for motor-speech acquisition is not clear, the results obtained in this study provide some support for the use of PROMPT in managing motor speech impairments associated with CP. Further research evaluating the use of this technique with a larger sample size and participants with differing levels of impairment is recommended to further develop our understanding of using this approach with children with CP.

Declaration of interest

The authors report no conflicts of interest.

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