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Spatial Characteristics of Jaw Movements During Chewing in Children with Cerebral Palsy: A Pilot Study

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Abstract

This study compared jaw motion between children with cerebral palsy (CP) and their typically-developing (TD) peers during chewing. The jaw movements of 11 children with spastic CP (GMFCS levels II–V) all of whom were exclusively oral feeders with no reported clinical issues with feeding [mean age = 7.49 (2.30) years; 7 males, 4 females] and 11 age- and sex-matched TD peers [mean age = 7.54 (2.35) years] were recorded using optical motion capture. Participants chewed five trials of three different consistencies, including puree, mechanical soft, and solid. For each chewing sequence, the path distance (total amount of distance traveled by the jaw), average jaw speed, and working space (total 3-dimensional size of the jaw movements during chewing) were calculated. The CP group had greater path distances for mechanical soft and solids ($p < 0.001$) and larger working spaces ($p < 0.001$) than the TD group. Consistency differences were also found with path distances increasing for both groups with increased bolus consistency ($p < 0.001$). Puree was chewed most slowly for both groups ($p = 0.05$) and was associated with smaller working space than the other consistencies for both groups ($p < 0.001$). The TD group demonstrated slower speeds for mechanical soft as compared to solids ($p = 0.05$), a finding which was not observed in the CP group. The results suggest children with CP showed jaw movement differences during chewing despite being exclusive oral eaters with no reports of clinical feeding or deglutition disorders. Food consistency also influenced jaw movements in both children with CP and their TD peers.

Keywords

De-glutition; De-glutition disorders; Chewing; Kinematics; Cerebral palsy; Children

Introduction

Cerebral palsy (CP) is a heterogeneous group of neurological disorders resulting in impairments in multiple domains, including movement, sensation, feeding, deglutition,

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communication, and cognition. The prevalence of disordered feeding varies across studies and severity classifications but estimates suggest up to 90% of preschool children with CP may have difficulty with oral intake [1] and 85% of preschool children with CP present with some degree of oropharyngeal dysphagia, despite the lack of a formal diagnosis [2]. These prevalence numbers suggest that feeding and deglutition disorders may be evident in children with even mild oromotor impairments [3, 4].

The relationship between oromotor biomechanics and feeding ability is largely unknown in this population; however, it has been posited that many of these feeding deficits are linked to oral motor difficulties [1, 5]. Most research in feeding in children with CP relies on either the prevalence of disordered feeding (see [6] for review) or descriptive reports and ratings of feeding and deglutition behaviors (e.g., feeding behavior at tableside [7, 8]), though one study has examined the mandibular muscle activation during chewing in this group [9]. Findings from descriptive reports suggest that children with CP may have a variety of early- to later-appearing feeding concerns including increased frequency of coughing and choking, difficulty with self-feeding [4], and a delayed introduction to solid foods as compared to their typically-developing peers [4, 10].

What is known about oromotor performance in individuals with CP is primarily based on clinical observation and scored using standard assessments or surveys. Findings suggest that over 80% of children with CP have at least some degree of oral motor dysfunction [11], which can result in poor lip seal, reduced tongue movements [5], and immature jaw movements [10]. However, to date, no known study has quantified the underlying biomechanic characteristics of oromotor performance using movement kinematics during chewing in this population.

The current preliminary study aims to examine the biomechanic properties of jaw performance during chewing in children with CP with no clinical feeding disorders. Quantifying the movement kinematics (i.e., performance characteristics) of jaw motion during chewing will allow researchers and clinicians to better understand the nature of oromotor performance underlying feeding ability in this population. What little is known about chewing behavior in individuals with CP is primarily based on visual observations of the chin during chewing [3]; however, recent work suggests that visual observations of the chin during chewing, even by trained clinical observers, do not always accurately reflect all aspects of jaw motion [12]. Therefore, the kinematic representations of movement, which are sensitive to small, fine-grained movements (e.g., up to 0.1 mm in accuracy) will provide much needed complementary information about the biomechanics of jaw motion during chewing in children with CP.

Recent research using kinematic methods to study oro-motor biomechanics of speech production in children with CP suggests difficulty with the timing and gradation of oral muscle activation [13], articulatory overshoot during speech [14], and reduced coordination [15]. Although chewing and speech are distinct tasks it is plausible that similar motoric deficits are present during chewing given the shared effectors across tasks.

The purpose of this investigation is to describe the characteristics of jaw motion for chewing in children with CP, *with no known feeding disorders*, and their typically-developing peers across three consistency categories. Consistency management plays a primary role in assessment and treatment of feeding and deglutition disorders; however, only a small number of descriptive studies have investigated the influence of bolus consistencies on chewing in children with CP and results are variable [1, 3]. This preliminary study is a first step in elucidating the role of oromotor biomechanics during chewing in children with CP. The rationale for only including children with no known feeding disorders was to allow for a more clear comparison between children with CP and their TD peers and to determine how food consistency might impact jaw movements in children with no known oromotor deficits. Furthermore, identifying compensatory behaviors in children with CP and no known feeding disorders in response to potential subclinical oromotor impairments will provide a better understanding of oromotor performance in this population.

The aims of the current study are to (a) compare the jaw movements of children with CP and their typically-developing (TD) peers during chewing and to (b) characterize jaw movements for both groups across different food consistencies. We hypothesize that jaw motion for chewing in children with CP will be characterized by increased speed, path distance (the total distance traversed by the jaw), and jaw working space when compared to their typically-developing peers. Furthermore, based on previous findings [16, 17] we hypothesize that solid foods will be chewed with greater speed, path distance, and working space as compared to puree and mechanical soft consistencies.

Method

Participants

Participants were recruited from local and regional clinics and local schools in San Diego, CA for this preliminary study. Recruitment focused on collecting a representative sample of children with CP that was not biased for the presence of speech, language, and/or feeding problems. Inclusion criteria for the current study were that children had a medical diagnosis of CP and were oral feeders. Eleven children with spastic cerebral palsy, all of whom were exclusively oral-eaters, with no parent-reported feeding or deglutition difficulties, participated in this study. The participants with CP ranged in age from 3 to 11 years and varied in the severity of their gross motor impairments, as shown in Table 1. Eleven age- and sex-matched TD peers with no history of neurological, speech, language, or hearing disorders were also enrolled and served as control participants. Participants with CP were classified by a pediatric SLP (first author) on both the GMFCS [18] and the CFCS [19]. An oral mechanism screening (OSMSE-3; [20]) was used to determine if any of the participants had structural changes or differences to the oral cavity that might affect chewing. All participants had expected dentition for their age and no participant had any structural differences in the oral cavity that might impact chewing. The children in this sample were born between 2002 and 2009 and were representative of Southern California in regards to socioeconomic status and race.

Kinematic Recordings of Jaw Motion

Jaw movements were recorded using an eight-camera optical motion capture system (Motion Analysis, Ltd.). Fifteen reflective markers were placed on each participant's face as shown in Fig. 1 [12, 14, 15]. Three spherical reflective markers, approximately 2 mm in diameter, were placed on the jaw using double-sided adhesive hypoallergenic tape. The first marker was placed at the center of the mandible just below the mental protuberance. The other two reflective markers were placed approximately 2 cm to the left and right of the center marker, above the platysma. Although three jaw markers were recorded, data from only the left-most or right-most marker was analyzed to reduce the potential for flesh-point tracking error [21].

A rigid plate with four reflective markers was also placed on the forehead. These reference markers were used to subtract head movement from the movement traces of the jaw markers and used to establish an anatomic coordinate system as well as reduce motion artifacts during post-processing of the kinematic data [22, 23].

Digital video and audio signals, aligned with the movement data, were recorded and used to identify the target jaw movements.

Chewing Tasks

It is well documented that jaw motion for chewing, and resultant bolus breakdown, is highly influenced by the consistency of the food being chewed, even in young children [16, 17]. Therefore, each participant was asked to eat at least five trials of the following consistencies: puree (applesauce), mechanical soft (banana), and solid (Cheerios®). Cheerios® were selected as the solid consistency because their size is standardized, they are recognizable food stuff popular with children, and they are free of many common allergens. Further, unlike other larger food stuff (e.g., pretzel or cookie), the Cheerios® did not need to be broken down into a small enough piece to place in the mouth thereby avoiding measurement problems related to modifying a solid-state bolus. Bolus size was controlled between trials, consistencies, and participants and was operationally defined as 1 teaspoon of applesauce, 1 slice of banana (approximately 1.5–2 mm in thickness), and 3 Cheerios®. Participants were asked to swallow the entire bolus before beginning the next bolus trial. Three participants with CP ate four trials of banana (mechanical soft). One participant with CP refused Cheerios® and one TD participant refused the puree consistency because he disliked applesauce.

Data Analysis

Each chewing trial was identified and parsed in Cortex (Motion Analysis, Ltd.) by a trained laboratory assistant following previously established guidelines [16, 17]. For most children, the food was placed inside the mouth, on the tongue and behind the front teeth by a trained research assistant. For a smaller number of older children, particularly for the TD peers, the food was placed inside their mouth independently, under the direction and supervision of the first author or a trained research assistant to ensure all the food was placed on the tongue and behind the front teeth. The feeding status (self-fed vs fed) was not believed to influence the chewing movements because the bolus size was controlled across participants and trials and the children who were fed had the food placed in the same area (on the tongue and behind

the front teeth) as the self-fed group. Further, the onset and offset of chewing sequence were discarded from the final analysis based on the parsing rules for each sequence (see below).

Each chewing sequence was parsed by a trained laboratory assistant based on visual observation of the video recording. The beginning of the sequence was defined as the point of lip closure after the food was placed inside the mouth and the spoon had been removed. The end of the sequence was defined as the beginning of laryngeal elevation, as per trained visual judgment, which represented the start of deglutition. The mid-90% of the puree trials and mid-80% of the trials with mechanical soft and solids were then analyzed. The mid-80% and mid-90% of the trials were analyzed to eliminate any jaw movements associated with bolus positioning and/or the swallow [17]. Ten percent of the data was re-coded to check for reliability. There was 94.7% agreement of the presence of chewing. The duration of the chewing sequences analyzed by the two coders was correlated at $r = 0.92$, $p < 0.05$.

Once the data sequences were parsed, they were analyzed using SMASH [24] to determine path distance (the total linear distance traveled by the jaw during the trial), the average speed, and volume jaw working space (the amount of 3D space used by the jaw during the chewing trial, further detailed below). To obtain the jaw working space, the three-dimensional space of the jaw movement was fit with a 2-standard deviation ellipse (see Fig. 2). The volume of the calculated ellipse was then calculated to obtain the measure of jaw working space. Univariate analyses were completed on each variable. The jaw working space data were skewed so the data for that variable were log-transformed before undergoing further analysis. Table 2 describes each kinematic variable and its functional clinical interpretations.

Statistical analyses were conducted with multilevel models because they account for missing data and unequal trial numbers. Separate multilevel models examining the effect of Group (CP, TD) and Consistency (Puree, Mechanical Soft, Solid), Age, Group $\times$ Consistency, and Group $\times$ Age were conducted using SAS PROC MIXED (SAS 9.3; [25]) on each kinematic variable (distance, average speed, working space) with participant as a random variable. Post-hoc analyses were conducted using Least Mean Squares with Bonferroni correction.

Results

Path Distance

Figure 3 shows the group and consistency differences for path distance. A significant main effect of Age [$F(1, 18) = 10.79$, $p < 0.01$, $\eta^2_{\text{partial}} = 0.36$] demonstrated that path distance decreased 4.39 mm per year of age. There was no significant main effect of Group. There was a significant main effect of Consistency [$F(2, 35) = 467.82$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.99$] and a significant Group $\times$ Consistency interaction [$F(2, 35) = 10.72$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.36$]. Post-hoc analysis revealed that for both the mechanical soft and solid consistencies, the children with CP had higher path distances than their TD peers. For both groups, puree had significantly smaller path distances as compared to mechanical soft and both mechanical soft and puree were chewed with significantly smaller path distances than

for the solid consistency. There was no group difference for the puree textures or a significant Group $\times$ Age interaction.

Average Speed

There was no significant main effect Age or Group and there was no significant Group $\times$ Age interaction. There was a significant main effect of Consistency [$F(2,35) = 252.02$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.99$] and a marginally-significant interaction of Group $\times$ Consistency [$F(2,35) = 3.11$, $p = 0.057$, $\eta^2_{\text{partial}} = 0.17$] as shown in Fig. 4. Post-hoc analyses showed that for the TD group, puree was chewed with significantly slower speeds than for mechanical soft, which, in turn, was chewed with significantly slower speeds than solids. Children with CP chewed puree with significantly slower speeds than mechanical soft and solid, with no significant difference in speed between mechanical soft and solids.

Working space

Working space differences are shown in Fig. 5. There was a significant main effect of Age [$F(1, 18) = 7.64$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.23$] revealing that jaw working space decreased 0.99 mm³ with each year of age. There was a significant main effect of Group [$F(1, 18) = 44.55$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.80$] with the CP group having greater overall working spaces than the TD group. There was also a significant main effect of Consistency [$F(2, 35) = 247.52$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.99$]. Both groups chewed puree with significantly lower working spaces than for the mechanical soft and solids, which were not significantly different. There was no significant Group $\times$ Consistency or Group $\times$ Age interaction.

Discussion

The purpose of this investigation was to evaluate the biomechanic properties of jaw performance during chewing in children with CP with no known feeding or deglutition disorders, and compare their findings to their age-matched peers across three consistency categories. Although this is a preliminary study on a specific group of children with CP, the results suggest that this group, in general, had greater jaw path distances and working space than their TD age-matched peers. Interestingly, jaw speed did not vary significantly between the two groups. These group differences confirm previously suggested hypotheses that children with CP, and no clinical feeding disorders, have altered oromotor performance while eating [10]. Consistency also played a significant role for both groups across all measures although the influence of consistency varied between groups and measures suggesting children with CP and their TD peers differ in their ability to manage various consistencies.

The observed group differences in jaw movement kinematics (i.e., increased path distances and larger estimates of working space for the children with CP) may suggest that children with CP require larger and/or additional movements in order to chew food in preparation for the swallow as compared to their TD peers. Similar kinematic descriptions of jaw performance during chewing have been reported in very young TD children and have been

interpreted as evidence of immature chewing patterns [16, 17]. Specifically, common age-related developmental changes in jaw performance include a reduction in movement path distance and working space as well as a reduction in movement speed as children purportedly hone in on the most efficient motor pattern.

The differences in chewing movement between groups in the current study are particularly striking because all of the children with CP are oral eaters and ranged in the severity of their gross motor impairments. These results quantitatively suggest that children with no reported clinical feeding difficulties may have subclinical biomechanic differences in jaw performance during chewing that were not otherwise detected clinically.

Findings from the current investigation also suggest that consistency plays a significant role in jaw performance for chewing in both children with CP as well as their TD age-matched peers albeit to a different degree. For example, an expected increase in path distance was seen with an increase in consistency (see Fig. 2) suggesting that consistency similarly influences path distance for both groups; however, the children with CP had greater path distance for mechanical soft and solid consistencies than their typically-developing peers. This finding could be interpreted to suggest that the children with CP required more effort to breakdown the mechanical soft and solid consistency foods than their typically-developing peers; an outcome that confirms an earlier report that solid consistencies are particularly difficult for some children with CP [26].

In contrast, path distance was similar between the two groups for the more basic pureed consistency, which could be interpreted to suggest that pureed food did not challenge the system in a similar degree. The observed consistency differences confirm previous findings which suggest that children with CP with mild oral motor involvement (similar to the current cohort), may have feeding difficulties that are consistency-specific whereas children with moderate or severe oral motor involvement generally have difficulty with all textures (e.g., solids, mechanical soft, puree) [1].

Taken together, the current findings suggest children with CP have biomechanic differences in jaw performance during chewing when compared to TD age-matched peers. These findings also appear to parallel reports of reduced oromotor performance during speech production including descriptions of increased lip and jaw displacements [14] and reduced coordination [15]. These articulatory differences may account for the speech deficits commonly observed in this group, including a slower speaking rate [14] and reduced intelligibility [15]. Although speech and chewing are uniquely different tasks and the underlying neural control is arguably distinct [27], the findings suggest that the impact of impaired movements caused by CP has the potential to affect motor ability across a variety of tasks. Future work investigating the biomechanic properties of oromotor performance across a wider variety of tasks including both speech and chewing in a larger sample of participants is warranted.

Clinical Implications and Limitations

The current findings suggest that children with CP and no clinical feeding disorders may have underlying subclinical biomechanic differences in jaw performance for chewing,

resulting in altered chewing patterns, despite typical clinical feeding behavior. The finding of excessive movements during chewing lends additional support for the proposal that children with CP may expend more energy while eating [26]. Similar to previous studies (see [17] for review), findings from the current investigation suggest that consistency influences jaw performance for chewing in children with CP and their age-matched peers. As a result, feeding skills should be assessed across multiple consistency types as these recommendations are important for safety, food acceptance, and energy expenditure considerations.

Of course, chewing requires gradient jaw control to adequately macerate food with the teeth in preparation for the swallow; however, other anatomic and oromotor factors including the structural integrity of the teeth, adequate occlusal alignment, and tongue control also arguably play an important role (see [28] for an overview). Although the oromotor screening in this investigation revealed no unusual differences in the structural integrity or alignment of the teeth; the current study does not include descriptions of tongue movement during chewing as lingual movement is difficult to study given its relatively obscured position in the oral cavity. Furthermore, the screening of feeding disorders in this cohort was accomplished through parental report. Future work should include a more formalized feeding screening. Finally, the end of the chewing sequence was noted by the visual judgment of laryngeal elevation, although clinically relevant, use of a more objective identification measure of the chewing sequence may be useful in future studies.

The current preliminary study is the first step in understanding the underlying biomechanic characteristics of jaw motion for chewing in children with CP. Future studies should examine chewing rate and durational measures of chewing performance at the biomechanic level as well as include a variety of consistencies and bolus sizes. Additionally, studies should include larger groups of children with CP to determine if there is a relationship between the severity of oromotor biomechanic differences and physical impairments across other motor systems, and to determine if the severity of the oromotor differences observed during chewing translates into later appearing oromotor behaviors for predictive purposes.

Of additional interest would be the inclusion of children with clinical feeding disorders secondary to CP which would provide insight into the biomechanic underpinnings of feeding difficulties in this population. Further, the inclusion of clinical assessment of feeding as well as manual skills (e.g., MACS scores [29]) would be useful in more broadly characterizing the feeding difficulties in this population. Finally, attempts to include descriptions of tongue movements during chewing will provide a more complete description of the underlying biomechanic characteristics of oromotor movement during chewing in this population.

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Fig. 1. Marker set up on a participant (*top left*), 3D model of the face (*top right*), and movement trace of the jaw marker after subtracting head movement (*bottom*)

Fig. 2.
Example of the two SD ellipse used to calculate the working space of jaw movements for a chewing trial

Fig. 3.
Path distance of the jaw movements for the three consistencies chewed

Fig. 4.
Average speed of the jaw movements for the three consistencies chewed

Fig. 5.
Working space of the jaw movements for the three consistencies chewed

Table 1

Participant information, including age, sex, GMFCS level [18], CFCS level [19], and age of age-matched typically-developing (TD) peer

Participant	CP type	Age	Sex	GMFCS	CFCS	Age of TD peer
1	Spastic diplegia	3;8	M	III	IV	4;0
2	Spastic quadriplegia	4;8	F	V	II	4;7
3	Spastic (Dandy Walker Var.)	5;4	M	III	IV	5;7
4	Spastic diplegia	6;6	M	III	I	6;2
5	Spastic diplegia	7;1	F	IV	V	7;1
6	Spastic hemiplegia	7;5	F	I	II	7;4
7	Spastic diplegia	8;2	M	II	I	8;4
8	Spastic hemiplegia	9;0	M	III	I	9;0
9	Spastic diplegia	9;9	M	I	I	9;4
10	Spastic diplegia	10;2	F	II	I	10;10
11	Spastic quadriplegia	10;7	M	IV	I	10;11

Table 2

Definitions and functional clinical interpretations of the kinematic variables

Kinematic variable	Definition	Functional clinical interpretation
Path distance	The total amount of distance traveled by the jaw in 3-dimension during a chewing sequence	The amount of movement needed to break down a bolus
Average speed	The average speed with which the jaw moves during a chewing sequence	How fast or slow the jaw moves during chewing
Working space	The total size of the jaw movements in 3-dimensions during a chewing sequence	The range of motion of the jaw during chewing