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Three-dimensional kinematics of the upper limb during a Reach and Grasp Cycle for children

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ABSTRACT

The ability to reach, grasp, transport, and release objects is essential for activities of daily living. The objective of this study was to develop a quantitative method to assess upper limb motor deficits in children with cerebral palsy (CP) using three-dimensional motion analysis. We report kinematic data from 25 typically developing (TD) children (11 males, 14 females; ages 5–18 years) and 2 children with spastic hemiplegic CP (2 females, ages 14 and 15 years) during the Reach and Grasp Cycle. The Cycle includes six sequential tasks: *reach*, *grasp* cylinder, *transport* to mouth (T_1), *transport* back to table (T_2), *release* cylinder, and *return* to initial position. It was designed to represent a functional activity that was challenging yet feasible for children with CP. For example, maximum elbow extension was $43 \pm 11^\circ$ flexion in the TD group. Consistent kinematic patterns emerged for the trunk and upper limb: coefficients of variation at point of task achievement for *reach*, T_1 , and T_2 for trunk flexion–extension were (.11, .11, .11), trunk axial rotation (.06, .06, .06), shoulder elevation (.13, .11, .13), elbow flexion–extension (.25, .06, .23), forearm pronation–supination (.08, .10, .11), and wrist flexion–extension (.25, .21, .22). The children with CP demonstrated reduced elbow extension, increased wrist flexion and trunk motion, with an increased tendency to actively externally rotate the shoulder and supinate the forearm during T_1 compared to the TD children. The consistent normative data and clinically significant differences in joint motion between the CP and TD children suggest the Reach and Grasp Cycle is a repeatable protocol for objective clinical evaluation of functional upper limb motor performance.

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1. Introduction

The ability to reach, grasp, transport, and release objects is central to activities of daily living, such as feeding and grooming. Children with cerebral palsy (CP) often have difficulty with the timing and coordination of reaching movements [1] and the coordination of fingertip forces during grasp and release [2,3]. The severity of upper limb involvement in children with hemiplegic CP varies from mild clumsiness in fine motor control to fixed muscle contractures that limit active extension of the elbow, wrist or fingers, and supination of the forearm [4]. Therapeutic and surgical interventions primarily focus on improving muscle balance and wrist position to maximize hand function [5]; however, the

methods for characterizing specific upper limb motion deficits and measuring the functional outcomes of these interventions are varied and mostly subjective.

Upper limb function has traditionally been evaluated by the Bayley Motor Scale [6], Jebsen–Taylor Test of Hand Function [7], and Peabody Fine Motor Scale [8]. However, such tests only assess the quality of upper limb movement based on observational analysis and are not standardized for the CP population. The Erhardt Developmental Prehension Assessment [9] is standardized for children with CP, but it assesses the quality of upper limb movement based on observational analysis only and its scoring system is non-quantifiable. Recently, additional evaluative tools have emerged, including the Quality of Upper Extremity Skills Test (QUEST) [10], the Melbourne Assessment of Unilateral Upper Limb Function [11], and the Shriners Hospital for Children Upper Extremity Evaluation (SHUEE) [12]. These tools provide information concerning the quality of movement, are standardized for the CP population, and provide a quantifiable score of performance, yet they are lengthy, require the child

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to perform numerous tasks, and are based on subjective, observational analysis.

Motion analysis offers an objective method for quantifying movement and is considered the gold standard for evaluating lower limb function during gait in individuals with CP [13,14]. Motion analysis of the upper limb is more technically challenging due to the non-cyclical nature of functional use and the increased range and complexity of motion at the shoulder joint [15]. As a result, few researchers have used motion analysis to characterize upper limb kinematics until recently [14,16–21], and there remains no generally accepted or standardized evaluation protocol [22]. We propose the Reach and Grasp Cycle and the model described below to address these issues. The Reach and Grasp Cycle is a sequence of tasks that incorporates all major joints of the upper limb and simulates a functional task that is feasible yet challenging enough to reveal key motor deficits in individuals with movement disorders. Joint kinematics were calculated according to a variation of the method proposed by the Standardization and Terminology Committee of the International Society of Biomechanics (ISB) [23].

The purpose of this study was to assess the utility of the Reach and Grasp Cycle using three-dimensional motion analysis. Normative kinematic patterns of reaching, grasping, transporting, and releasing an object were characterized for 25 typically developing children, and upper limb kinematics are reported for two children with CP.

2. Methods

2.1. Participants

Twenty-five typically developing (TD) children and adolescents (11 males and 14 females, ages 5–18 years, mean age 11.0 ± 4.1 years) participated in this study. Participants had no history of orthopedic or neurological abnormalities. Two children with moderate, left-sided spastic hemiplegic CP (2 females, ages 14 and 15 years) were evaluated for comparison purposes. The protocol was approved by the Stanford University Institutional Review Board. Informed consent was obtained from the children's parent or guardian; written assent was acquired from children 7 years and older.

2.2. Experimental set-up

Light-reflective markers were placed on the child's torso and upper limbs at specific bony landmarks (Fig. 1A and B). Participants were seated comfortably at a height-adjustable table with the hips and knees flexed 90° and both feet flat on the ground. Both arms rested on the table so that the shoulder was in a neutral position, the elbows were flexed approximately 90° , the forearms were pronated, and the wrists were held in neutral with the palms flat on the table. A cylindrical cup (height: 12.5 cm, diameter: 5.5 cm) was placed at 75% of the participant's maximum reach. From the initial *start* position, each participant was instructed to *reach* forward and *grasp* the cup, *transport* the cup to his/her mouth to simulate drinking (T_1), *transport* the cup back to its original location (T_2), *release* the cup, and *return* his/her arm to the initial position. The phases and tasks of the Reach and

Grasp Cycle are displayed in Fig. 2. The TD participants were instructed to perform the task with the dominant hand; the patients with CP performed the task with the more impaired hand to assess the extent to which they deviated from the normal level of function. Three-dimensional marker position data were recorded from participants during a single Reach and Grasp Cycle after one to two practice trials using an eight-camera optoelectric motion analysis system recording at 60 Hz (Motion Analysis Corporation, Santa Rosa, CA), and filtered using a Butterworth filter with a cutoff frequency of 12 Hz.

2.3. Upper limb model

Joint kinematics were calculated according to a variation of the method proposed by the Standardization and Terminology Committee of the ISB, which defined a set of coordinate systems for various joints of the upper body based on the joint coordinate system [23]. The upper limb model (Fig. 1C) consisted of nine segments, including the trunk, right and left shoulder girdle, right and left upper arm, right and left forearm, and right and left hand, as previously described [24]. Shoulder abduction and flexion were described as "elevation" to minimize any ambiguity associated with clinical measurements, according to ISB recommendations. Additional details on the upper limb model can be found in [Supplementary Material](#).

2.4. Data analysis

Based on the model described above, UETrak software, Version 1.5.8 (Motion Analysis Corporation, Santa Rosa, CA) was used to calculate joint kinematics for eight primary motions of the trunk and dominant arm: trunk flexion–extension, trunk axial rotation, shoulder elevation, shoulder internal–external rotation, elbow flexion–extension, forearm pronation–supination, wrist flexion–extension, and wrist ulnar–radial deviation.

The velocity of the wrist marker defined the beginning and end of the Reach and Grasp Cycle. The onset of movement from the *start* position was identified as the first instant when the velocity of the wrist marker exceeded 5% of peak reaching velocity [16,20]; the end of the Cycle was signified by a decrease in wrist marker velocity to less than 5% of the maximum velocity upon returning the arm to the initial position. Each joint motion curve was normalized to 100% of the Reach and Grasp Cycle. There was a symmetric distribution for the normalized joint angle data, as evidenced by coincidence of the mean and median values. Therefore, the mean and standard deviation were plotted for every 1% of the Cycle using Matlab (MathWorks, Natick, MA) to create a normative database of upper limb kinematics during the Reach and Grasp Cycle.

2.5. Statistical analysis

The coefficient of variation (CV) was calculated for all eight kinematic parameters to determine the relative variability of the Reach and Grasp Cycle among TD children. Kinematic angles spanning -90° to 90° were corrected to $0-180^\circ$ to eliminate negative numbers before calculating CV. To determine the influence of age on upper limb kinematics, Spearman's rank correlation coefficients were computed between participant age and the eight joint motions. Kinematic values were compared at *start* (0% of Cycle), the points of task achievement at the end of *reach*, T_1 , and T_2 , and the end of *return* (100% of Cycle). The Holm–Šidák procedure was used to correct for multiple correlations. To assess repeatability of the Reach and Grasp Cycle, three trials were recorded during two testing sessions one week apart for a representative subset of seven TD children (3 males and 4 females, mean age: 11.2 ± 4.4 years). Intra-session and inter-session errors were calculated; the reliability of a given joint angle was measured by its standard error [25].



Fig. 1. Typically developing participant demonstrating the testing set-up and placement of the retro-reflective markers while (A) reaching forward to grasp the cup and (B) transporting the cup to the mouth. The segmental coordinate systems for the trunk and upper limb (C) using estimated joint centers as local origins: trunk (O_1), glenohumeral joint (O_2), elbow joint (O_3), and wrist joint (O_4).

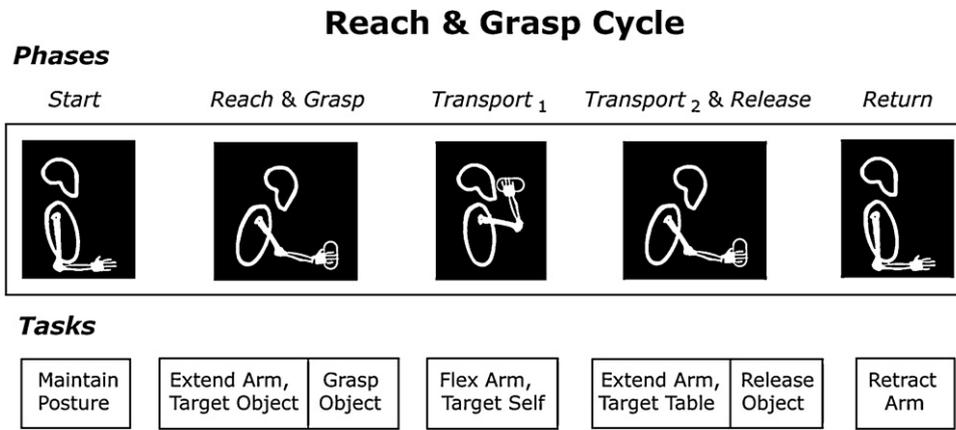


Fig. 2. Phases and tasks of the Reach and Grasp Cycle. *Reach* begins with the initial onset of movement and continues until the hand makes contact with the cylinder. *Grasp* lasts from hand–cylinder contact until lift-off from the table. The first object transport phase (T_1) is defined as the time from cylinder lift-off to when the hand is paused with the cylinder at the face. The second object transport phase (T_2) begins when the hand leaves the face and lasts until the cylinder touched the table. The *release* phase lasts from cylinder–table contact until the cylinder is fully released from the hand. The beginning of the *return* phase is initiated as the hand retreats from the cylinder and continues until the hand comes to rest at the starting position, thereby completing the Cycle.

3. Results

Consistent kinematic patterns emerged for each of the trunk and upper limb motions during the Reach and Grasp Cycle. Joint motions during the Reach and Grasp Cycle demonstrated low variability among typically developing (TD) participants (Table 1). The mean CV for all phases was .12.

Total joint excursion during the Reach and Grasp Cycle in the TD population was greatest for elbow flexion–extension ($80 \pm 11^\circ$), followed by pronation–supination ($49 \pm 12^\circ$), shoulder elevation ($41 \pm 10^\circ$), wrist flexion–extension ($37 \pm 11^\circ$), shoulder rotation ($19 \pm 6^\circ$), wrist deviation ($12 \pm 3^\circ$), trunk rotation ($7 \pm 3^\circ$), and trunk flexion–extension ($3 \pm 2^\circ$). Both children with cerebral palsy (CP) demonstrated increased trunk flexion–extension and trunk rotation, as well as reduced elbow flexion–extension excursion compared to the TD population.

There was a significant correlation between age and joint position at the point of task achievement for 3 of the 40 measures, after Holm–Šidák correction for multiple correlations: elbow flexion and wrist deviation at the end of T_1 ($\rho = .587$, $p = .0139$ and $\rho = -.601$, $p = .0119$, respectively) and pronation at the end of *return* ($\rho = .539$, $p = .0424$). The kinematic data were grouped together to form mean trunk and upper limb motion curves as shown in Fig. 3A–H. The mean ± 1 SD is plotted for the 25 TD children and the 2 children with hemiplegic CP. The complete normative dataset can be found in Supplementary Material.

Intra-session and inter-session errors in upper limb kinematics were calculated at the point of task achievement for seven TD children, as shown in Table 2. Mean intra-session errors ranged from 0.6° to 3.4° , and mean inter-session errors ranged from 1.6° to 4.8° .

Upper limb kinematics of the two children with moderate, left-sided spastic hemiplegic CP demonstrated substantial differences during the Reach and Grasp Cycle, i.e. greater than one standard deviation from the TD mean (Fig. 3A–H). Both children demonstrated increased shoulder internal rotation during *reach* and reduced elbow extension at the end of *reach* and T_2 . Throughout the Reach and Grasp Cycle, the wrist was held in a posture of increased flexion with a reduced arc of ulnar–radial wrist deviation. In addition, both participants demonstrated an increased tendency to actively externally rotate the shoulder and supinate the forearm when bringing the cylinder to the mouth (T_1) and to internally rotate the shoulder and pronate the forearm when transporting the cylinder back to the table (T_2). In contrast, the TD children maintained approximately 10° of shoulder internal rotation and 35° of forearm pronation during T_1 and T_2 .

Differences also emerged between the two participants with CP. Participant 1 sat with more trunk flexion and forward trunk rotation, and demonstrated increased shoulder elevation, wrist flexion, and ulnar deviation compared to Participant 2. Participant 1 used more forearm supination to bring the cylinder to her mouth during T_1 compared to Participant 2, likely due to her increased wrist flexion posture. Participant 2 sat in a more upright posture, had an increased arc of shoulder internal–external rotation, and held her wrist in increased radial deviation compared to Participant 1. Participant 2 also demonstrated increased forearm pronation during *reach* compared to Participant 1.

On physical examination, Participant 1 had reduced active range of elbow extension, wrist extension, and radial deviation, but she was able to actively supinate to neutral with strong effort, consistent with the kinematics. Participant 2 demonstrated a reduced active range of elbow extension, forearm supination, and wrist extension, which was also consistent with the kinematics.

Table 1

Coefficients of variation (CV) for trunk and upper limb kinematics during the Reach and Grasp Cycle. The CV data are presented for the set-up phases of *start* and end of *return*, as well as at the point of task achievement for the functional phases of *reach*, *transport₁*, and *transport₂*.

Joint motion	Start	Reach	Transport ₁	Transport ₂	Return
Trunk flexion–extension	0.11	0.11	0.11	0.11	0.11
Trunk rotation	0.05	0.06	0.06	0.06	0.05
Shoulder elevation	0.35	0.13	0.11	0.13	0.39
Shoulder rotation	0.09	0.06	0.11	0.08	0.09
Elbow flexion–extension	0.19	0.25	0.06	0.23	0.19
Pronation–supination	0.06	0.08	0.10	0.11	0.06
Wrist flexion–extension	0.16	0.25	0.21	0.22	0.15
Wrist deviation	0.05	0.03	0.05	0.04	0.05

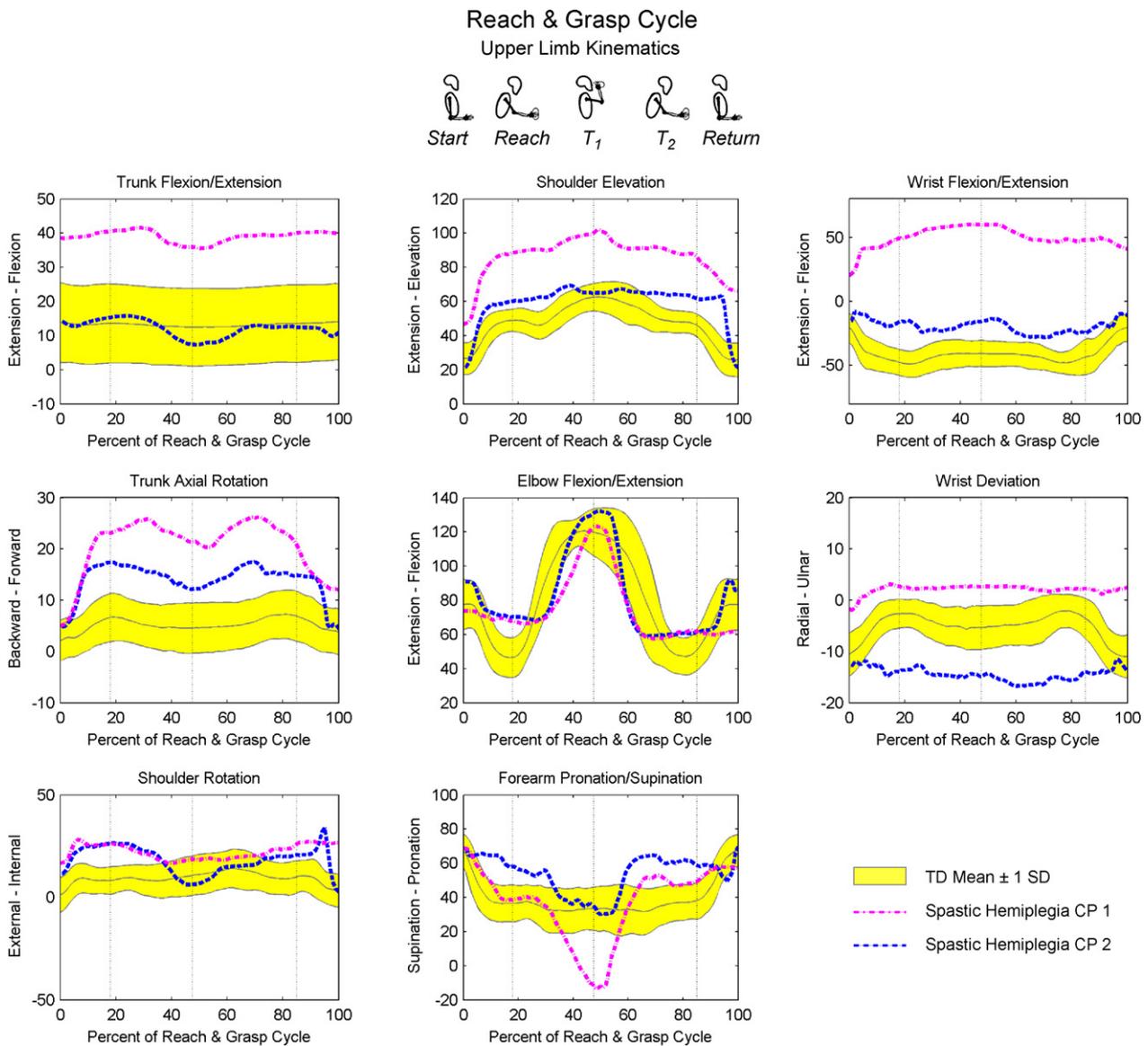


Fig. 3. Upper limb kinematics during the Reach and Grasp Cycle: (A) trunk flexion/extension; (B) trunk axial rotation; (C) shoulder internal/external rotation; (D) shoulder elevation/extension; (E) elbow flexion/extension; (F) forearm pronation/supination; (G) wrist flexion/extension; (H) wrist ulnar/radial deviation. Yellow band symbolizes the mean \pm 1 SD for the typically developing participants; the dashed lines represent patient data from two children with spastic hemiplegic cerebral palsy. The vertical lines at 18%, 48%, and 85% of the Reach & Grasp Cycle depict the point of task achievement for reach, T_1 , and T_2 , respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 2
 Intra-session and inter-session variability for a representative subset of 7 children (3 males and 4 females, ages 5–17 years, mean age: 11.2 ± 4.4 years). Values are reported in degrees for joint motions at five points during the Reach and Grasp Cycle. The mean intra- and inter-session errors are reported in the last column.

Joint motion	Start		Reach		Transport ₁		Transport ₂		Return		Mean error	
	Intra	Inter	Intra	Inter	Intra	Inter	Intra	Inter	Intra	Inter	Intra	Inter
Trunk flexion–extension	0.7	1.7	0.6	1.6	0.6	1.4	0.8	1.5	0.5	1.6	0.6	1.6
Trunk rotation	0.8	1.6	0.6	1.4	0.7	1.7	0.9	1.6	1.0	1.8	0.8	1.6
Shoulder elevation	0.9	3.5	1.0	2.5	2.7	3.0	1.0	2.2	2.6	3.5	1.7	2.9
Shoulder rotation	2.1	3.6	0.9	2.2	3.2	5.4	1.9	2.6	1.8	3.6	2.0	3.5
Elbow flexion–extension	1.1	3.5	2.2	3.7	2.5	3.6	2.2	3.7	3.8	4.4	2.4	3.8
Pronation–supination	2.4	3.1	2.7	4.6	4.7	7.0	3.7	5.8	3.3	3.5	3.4	4.8
Wrist flexion–extension	2.7	4.0	3.3	4.6	2.5	4.9	3.5	4.9	3.3	4.3	3.0	4.5
Wrist deviation	0.8	2.1	0.7	2.0	1.4	2.1	0.8	1.9	0.8	2.1	0.9	2.0

4. Discussion

The Reach and Grasp Cycle was designed for objective quantification of upper limb motion in children. The utility of the Reach and Grasp Cycle was demonstrated by the consistent

kinematic patterns among the typically developing (TD) children, and the clinically significant differences in joint motion between the children with cerebral palsy (CP) and the TD participants. The Reach and Grasp Cycle provides a quantitative analysis of motor deficits during a functional task.

Several studies have used three-dimensional motion analysis to examine upper limb motion in children with CP; although these studies have varied in the tasks performed, they have all incorporated some aspect of reaching or grasping [14,16,17,19–21]. The Reach and Grasp Cycle represents a natural and functional behavior, such as reaching for a cup and bringing it to the mouth. Providing a functional context to a task has been shown to improve the quality of reaching movements in children with spastic hemiparesis [26]. In addition, the Reach and Grasp Cycle was meant to be feasible for children with motor deficits and was not intended to assess the extreme ranges of motion. Thus, the cylinder was placed at 75% of each child's maximum reach so that the total joint excursion for each motion was less than the normal maximum range of motion.

Kinematic patterns were highly consistent among TD children during the Reach and Grasp Cycle, demonstrating a low mean coefficient of variation ($CV = .11$) for the functional phases of *reach*, T_1 , and T_2 . Despite the increased range and complexity of motion possible during unrestrained reaching movements, certain characteristic features exist, such as approximately straight hand trajectories with bell-shaped velocity profiles, tight phase-couplings of the shoulder and elbow joints, and consistent patterns of muscle activity [27–30]. All CV values at point of task achievement for the functional phases of the Reach and Grasp Cycle were less than .28. The CV for elbow flexion–extension was lowest at the end of T_1 ($CV = .06$) with an average elbow flexion angle of $123 \pm 7^\circ$, suggesting that elbow flexion when drinking or bringing other items to the mouth is highly consistent among individuals. This consistency is also likely related to limb-size effects, i.e. the final T_1 position is anatomic (hand to mouth), rather than dependent on external parameters, such as cup position.

For the non-functional phases of *start* and *return*, the variation in kinematic patterns among TD children was slightly greater than the functional phases (mean $CV = .13$). While an effort was made to standardize the set-up, the larger CV's for shoulder elevation between TD participants at the start and end of the Reach and Grasp Cycle (.35 and .39, respectively) suggest the initial and final positions of the participants could have been monitored more closely.

There was a significant correlation between age and joint position at the point of task achievement for 3 of the 40 kinematic measures during the Reach and Grasp Cycle: elbow flexion and wrist deviation at the end of T_1 , and pronation at the end of *return*. Younger children had less elbow flexion and less wrist radial deviation at the end of T_1 . Based on a linear fit of the data, the amount of change in elbow flexion and wrist radial deviation over a period of 5 years would be 4.6° and 2.5° , respectively, comparable to inter-session error (Table 2). At the end of *return*, older children assumed a more pronated forearm position, reflecting better compliance with the instructions to “return his/her arm to the initial position”, i.e. palms flat on the table. The change in pronation over a 5-year period based on a linear fit of the data would be 7.0° . In a similar study, Petuskey et al. [18] analyzed three-dimensional upper limb motion of 51 TD children during five simulated activities of daily living and found statistically significant age group-related differences in trunk flexion–extension, elbow flexion–extension, and forearm pronation–supination. However, none of these kinematic differences were greater than 10° ; the authors deemed a difference of less than 10° as clinically irrelevant. Furthermore, children older than 4 years of age have been shown to use the same proportion of elbow extension and trunk excursion as adults during reaching [31]. For these reasons, the kinematic data were grouped to form the mean curves shown in Fig. 3A–H.

The two children with CP demonstrated an increased range of trunk motion and increased wrist flexion throughout the Reach and Grasp Cycle, with increased shoulder internal rotation during

reach, and decreased elbow extension during the *reach* and T_2 phases. Participant 2 also demonstrated reduced forearm supination during *reach* and T_2 compared to the TD children. These findings are consistent with similar studies of upper limb kinematics [16,17,21], either compared to TD children [16,17] or with respect to the less-impaired arm of the children with hemiplegic CP [21]. The upper limb motion of the children with CP reported here is also consistent with typical patterns of spastic joint deformities, including shoulder internal rotation, elbow flexion, forearm pronation, wrist flexion and ulnar deviation [5]. Moreover, the kinematic data reported also provide information regarding dynamic motion disorders present in CP. For example, both participants demonstrated an increased tendency to actively externally rotate the shoulder and supinate the forearm when bringing the cylinder to the mouth (T_1) and to internally rotate the shoulder and pronate the forearm when transporting the cylinder back to the table (T_2). For Participant 1, the increased active forearm supination while bringing the cylinder to the mouth was compensatory for her increased wrist flexion posture. For Participant 2, with decreased supination during *reach*, the active forearm supination while bringing the cylinder to the mouth served to posture the forearm within normal limits.

Recent studies of upper limb treatment, e.g. botulinum toxin A injections [32], constraint-induced movement therapy [33], and corrective surgery [34], have used a variety of quantitative measures to assess outcome. The upper limb Reach and Grasp Cycle has the potential to offer effective and standardized quantitative evaluation of pre- and post-intervention. In addition, these quantitative measures of upper limb function may help delineate diagnoses of different movement disorders, and thus, may be important in determining structure–function relationships between brain and motor abnormalities. In a group of 51 preterm children with CP, van der Heide et al. [20] found that an impaired quality of reaching was related to severity of brain lesions on neonatal ultrasound.

There are certain limitations that warrant consideration when interpreting the results of this study. Due to the complexity of the shoulder joint, only motion of the upper arm with respect to the ipsilateral side of the trunk was considered, i.e. glenohumeral motion. Acromioclavicular and scapulothoracic motions were not considered. Thus, the upper limb model presented here does not represent fully anatomically correct shoulder motion. In addition, the upper limb joint centers were estimated from external marker offsets. Although this is standard procedure for three-dimensional kinematic studies, soft tissue artifact and a lack of precise joint center offsets for the pediatric population contribute to systematic error. Future work will expand on the construct-validity of the Reach and Grasp Cycle for use in children with CP through correlation with the QUEST [10]. Standardization of the start and end positions requires further refinement, given the higher CVs. Although intra- and inter-session errors were low in the TD population, we recommend collecting at least three trials; a three-dimensional study of upper limb kinematics during reaching, grasping, and manipulating objects has shown moderate to good repeatability in children with CP [14].

In summary, the utility of the Reach and Grasp Cycle was demonstrated by the consistent kinematic patterns that emerged among the TD children, as well as the clinically significant differences in joint motion that arose between the children with CP and the TD children. The Reach and Grasp Cycle allows for objective quantification of upper limb motion in children.

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Conflict of interest statement

None of the authors have financial or personal relationships with other people or organizations that could inappropriately influence their work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2010.03.011.

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