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Research article

Analysis of motor characteristics of reaching movements in children with cerebral palsy

Leia B. Bagesteiro [a,*], Tamires L. Tellini [b], Liana E. Brown [c]

[a] Department of Kinesiology, San Francisco State University, San Francisco, CA, 94132, USA
[b] Universidade Federal do ABC, Santo Andre, SP, 09210580, Brazil
[c] Departments of Psychology and Kinesiology, Trent University, Peterborough, Ontario, Canada

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ABSTRACT

Studies confirm that children with cerebral palsy (CwCP) have difficulty with simple, everyday movements like reaching for objects. Accurate reaching requires that shoulder and elbow joints are coordinated to move the hand along a smooth path to the desired target location. Here we examined multijoint coordination by comparing reaching performance in the affected and unaffected limbs of CwCP (nine children, six girls and three boys, aged 8–10 years) to reaching performance in the non-dominant and dominant limbs of typically-developing age- and gender-matched control (CTR) children. The hypothesis was that CwCP would show the effects of coordination deficits in both their affected and unaffected limbs. All children performed two sessions (one session with each arm) of speeded reaching movements to three targets arranged to manipulate the required pattern of shoulder and elbow coordination. The movements were tracked with a motion tracker allowing us to assess the following measures: movement distance, duration, and speed, hand-path deviation from linearity, final position accuracy and precision, and measures of shoulder and elbow excursion. We found that CwCP made reaches that covered a greater distance and took more time, that their shoulder and elbow rotations were larger, and that their movements showed greater deviation from linearity than the movements performed by CTR children. Children with CP were also more variable than CTR children on every measure except movement duration. The pattern of shoulder and elbow rotation observed in the CwCP group represents a coordination pattern that is significantly different from the pattern used by CTR children and may represent a greater reliance by CwCP on proximal muscular control systems. The discussion section considers the role that the cortical-spinal system may play in multijoint coordination.

1. Introduction

When a child reaches out to grab a toy, the movements of the elbow and shoulder are selected and timed so that the hand moves to the target in a way that becomes increasingly direct, efficient, and graceful with learning and development. The learning and development of these central nervous system (CNS) signals depends on children's increasing ability to (1) select the movement that best suits their current goal, and (2) make good use of sensory feedback generated as the movement is performed [1,2]. Children with cerebral palsy experience difficulties with this learning and development process.

* Corresponding author.
E-mail address: lbb@sfsu.edu (L.B. Bagesteiro).

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Cerebral Palsy (CP) is a general term for a group of movement disorders that interfere with people's ability to move and maintain balance and posture. It has an incidence of 2/1000 births (moderate and severe incidence) in developed countries. In Brazil, data from the Department of Child Neurology at the University of São Paulo point to an incidence of 7/1000 births and an estimated 26 thousand new cases per year. Cerebral Palsy is typically diagnosed in the first year of life as infants fail to meet motor developmental milestones. It is caused by brain damage that can happen before, during or after birth, and that interferes with motor development and learning in infants and across the lifespan. CP typically presents with upper motor neuron signs including hypertonia, spasticity, hyperreflexia, either unilaterally or bilaterally, and it can lead to hemiplegia or quadriplegia [3]. Studies confirm that children with CP (CwCP) have difficulty using their affected limbs for skillful activities that involve the precise control of voluntary movements, like reaching and grasping. Muscle activity during movement is characterized by abnormal patterns of excitation and inhibition [4–6].

In typically-developing children and adults, performing smooth, graceful reaching movements, such as reaching for objects, involves muscular actions that both move the hand and prepare it for interacting with items in the environment. The ability to control these interactions, however, is usually asymmetrical, such that the dominant limb shows better coordination than the non-dominant limb [3,7]. These asymmetries complicate the appearance of the motor signs of CP. Asymmetrical control may encourage CwCP to rely almost entirely on their non-affected hand to perform activities of daily living (ADL) and may lead to the development of exaggerated asymmetries between the unaffected and affected hand and compensatory movement patterns as CwCP develop. Past examination of the kinematics of reaching by CwCP found that, in comparison to the non-affected arm, reaching with the affected arm is slower, of longer duration, includes a higher number of submovements, and has reduced spatial precision both in the movement path and endpoint [4,8]. Mackey et al. [9] found that when children reached for targets on their faces, CwCP engaged in compensatory trunk flexion when their CP-affected limb failed to acquire the target due to restricted elbow extension.

CP also interferes with movement-related sensory processing. Children with CP can use ongoing visual feedback to correct for spatial errors on the fly [10], but CP-related sensory deficits reduce the effectiveness of this strategy [3,11]. Chang et al. [8] found that movement smoothness and movement duration were the most sensitive measures distinguishing CwCP performance from age-matched controls in a self-paced reaching task, especially when the task emphasized accuracy, where the use of sensory information to correct visual-spatial error is paramount.

In general, the differences between reaching by CwCP and typically-developing children can be characterized by low speed, inadequate coordination, longer movement duration, and greater movement variability [4–6,12–14]. These difficulties can affect daily and recreational activities, sometimes leaving CwCP more vulnerable to emotional and behavioral problems [12–14]. As a result, there is need to properly describe changes in movement functioning and develop specific rehabilitation techniques for this population [15]. This study aims to describe differences in multijoint coordination during arm reaching movements in CwCP compared to age-matched control children. A secondary objective is to verify whether the difference between the hemiparetic (affected) and unaffected limbs in children with CP is larger than the difference between the left (non-dominant) and right (dominant) limbs of control children. Our hypothesis is that reaching movements in CwCP will be characterized by coordination deficits in both affected and non-affected limbs in comparison to control children.

2. Materials and methods

2.1. Design

This study used a 2-group (children with CP, typically-developing children) by 2-arm (affected and unaffected arm of CwCP, dominant and non-dominant arm of typically-developing children) by 3-target direction (45-, 90-, 135-degree) mixed factorial design (Fig. 1). Group, the between-participants factor, was composed of both typically-developing control (CTR) children and CwCP as described in the participants section. All participants completed the reaching task with both arms, a within-participants factor, however, the manner in which the arm factor is characterized is nested within groups. All participants made reaching movements

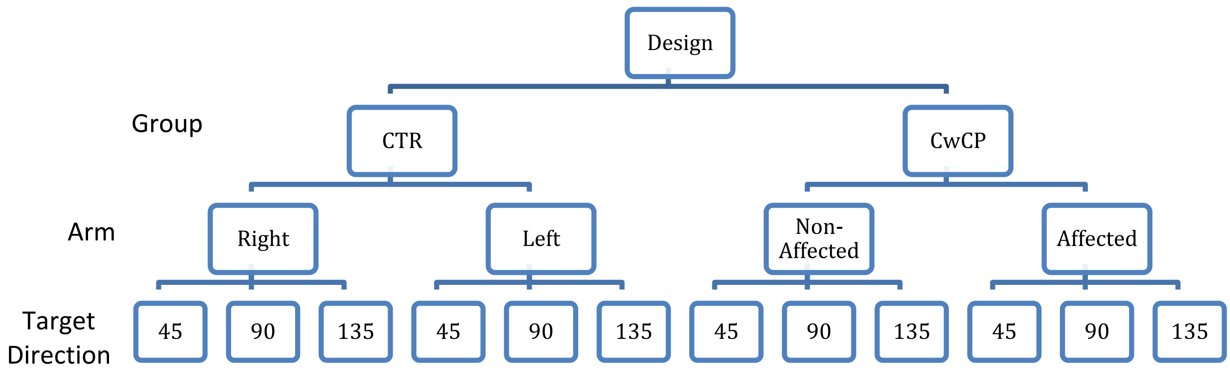

Fig. 1. Experimental design.

toward three targets arranged in three different directions (45-, 90-, and 135-degree relative to the start position; shown in Fig. 2B), a within-participants factor. This manipulation is known to vary the degree to which the reaching movement demands inter-joint coordination and is an effective way to vary movement difficulty. Movements to the 45-degree target are performed easily with very little involvement of the shoulder. As target angle increases, shoulder involvement is known to increase, placing greater demand on the CNS systems involved in elbow-shoulder coordination, and leaving predictable effects on movement performance [16–19]. Each child visited the laboratory once, and performed 27 trials to familiarize with the task, followed by 72 trials (experimental session). Each child completed two experimental sessions on the same day, one with each arm (i.e., right/unaffected and left/affected). The order of these sessions alternated across participants in the CTR group, while the CwCP group always started with the unaffected arm, as starting with the affected arm could cause discouragement at the beginning of the experiment [6]. The dependent variables (described in more detail below) assessed movement performance using measures of movement kinematics. Movement distance, duration, peak hand velocity and acceleration, deviation from linearity, and endpoint accuracy and precision were evaluated. We also looked at measures of movement execution by examining shoulder and elbow angular excursions and their relative excursion.

2.2. Participants

Participants were recruited from the outpatient rehabilitation clinics and local community. Two groups of participants (see Table 1) were included in the study. Children with CP (CwCP) were represented by a group of nine children diagnosed with CP (six right-arm affected, three left-arm affected), aged 8–10 years (six girls): mean (±SD) age (8.89 ± 1.05) years old, body mass (32.33 ± 5.96) kg, and body height (1.36 ± 0.08) m. All CwCP attended regular schools and were engaged in either individual or group physical therapy for at least one year prior to the study. The inclusion criteria for the CwCP group were that children be diagnosed with unilateral CP affecting upper-limb function with mild to moderate spastic hemiparesis resulting from unilateral brain dysfunction, with functional balance to sit, and cognitive and attention skills adequate to perform the experimental task. These inclusion criteria were screened through medical records review. The exclusion criteria for CwCP group participants were: (a) presence of severe visual impairment; (b) previous history of surgery on the upper limb and, (c) inability to complete the reaching movement.

The control group (CTR) included nine typically-developing children (six girls), aged 8–10 years: mean age (8.89 ± 1.05) years old, body mass (34.00 ± 8.14) kg, and body height (1.35 ± 0.08) m. Control children were selected to be age- and gender-matched to the CwCP participants. An inclusion criterion was that CTR children be right-handed. Manual preference was determined for CTR participants by observing their performance on ten different tasks [5]: drawing a picture, throwing a ball to a target, cutting with scissors, using an eraser, opening a box, using a plastic hammer, opening a locker with a key, using a pencil sharpener, taking the first card of a deck, taking balls from a box. For each task, the test object was positioned at the center of the table (i.e., mid-sagittal plane). The child was then asked to take the object and perform the relevant task. The hand used was recorded and used to determine hand quotient, the percentage of time the right hand was used as the dominant hand (HQ%; 5). For bimanual tasks such as cutting a sheet of paper with scissors or opening a box, the hand that mainly moved or was used to manipulate the scissors (as opposed to stabilize the paper or the box) was considered dominant. All CTR children performed at least nine out of ten tasks with their right hand (mean 10-task Performance Score = 97.78 ± 4.41; see Table 1). The exclusion criteria for the CTR group were: (a) concomitant clinical conditions (e.g., heart problem); (b) neurological problems; (c) degenerative muscle disorders (e.g., muscular dystrophy); (d) autism; (e) intellectual disability (e.g., Down's syndrome); (f) musculoskeletal problems (e.g., scoliosis); (g) poor or uncorrected visual acuity and h) premature birth (<37 weeks of gestation [7].

The study was approved by the *Universidade Federal do ABC* ethics committee and the informed consent form was read and signed by parents or legal guardians to allow the participation of the child in the study. Parents or family members were permitted to be

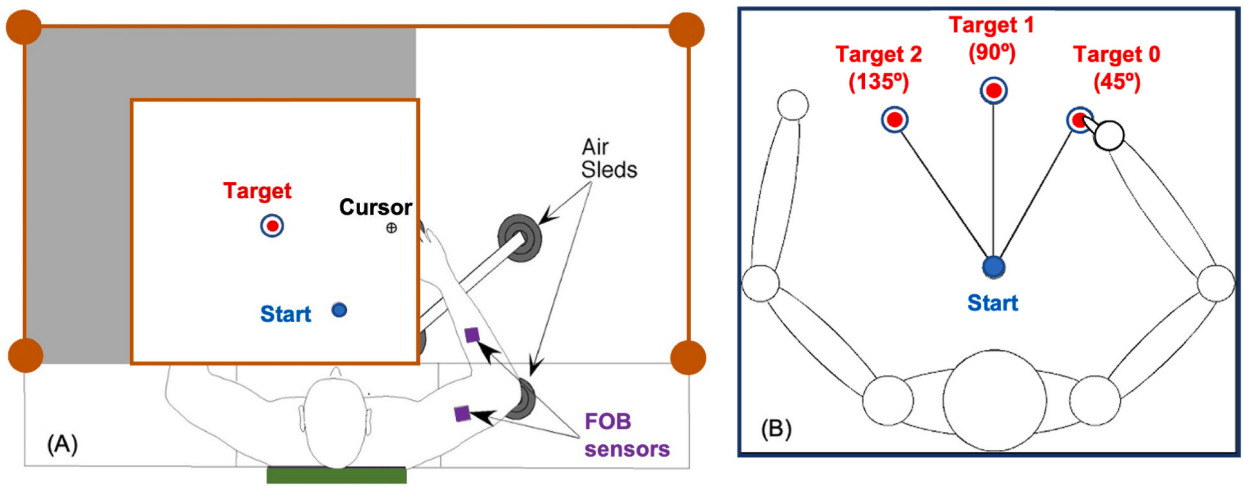

Fig. 2. (A) Experimental setup; (B) Target directions.

Table 1
Participants demographic characteristics.

Participant	Group	Sex	Age (years)	Mass (kg)	Height (m)	Affected side/10-task Performance Score**
1	CwCP	F	8	33	1.30	L
2	CwCP	F	8	20	1.23	R
3	CwCP	M	8	34	1.30	L
4	CwCP	F	8	29	1.35	R
5	CwCP	F	10	32	1.43	L
6	CwCP	M	10	33	1.46	R
7	CwCP	F	10	34	1.43	R
8	CwCP	M	10	33	1.35	R
9	CwCP	F	8	43	1.39	R
10	CTR	F	8	39	1.27	100
11	CTR	F	8	37	1.29	100
12	CTR	M	8	51	1.45	90
13	CTR	F	8	24	1.23	100
14	CTR	F	10	37	1.47	90
15	CTR	M	10	33	1.43	100
16	CTR	F	10	28	1.34	100
17	CTR	M	10	29	1.34	100
18	CTR	F	8	28	1.30	100

CwCP: child with CP; CTR: matched control child; F: female; M: male; L: left; R: right. **10-task Performance Score: 100 = all ten tasks performed with the right hand.

present during the experiment in order to make the children more comfortable.

2.3. Measurement of reaching movements

Children were positioned in front of a horizontal projection screen and table with their right and left arms resting on the table (Fig. 2A). The wrist and fingers were immobilized by a wrist orthosis and supported by a friction-less air jet system (Fig. 2B; [17,20]). Participants sat on a chair with 5-point harness to restrict movement of the trunk, and the height of the chair was adjusted so that children were at the ideal height to see the targets, start location and cursor projected on the horizontal screen clearly.

Two 6-degree-of-freedom movement sensors (Flock of Birds, Ascension Technology) were used to monitor the position and orientation of the arm and forearm during reaching performance. Each sensor was attached to a segment of the upper limb (positioned at midpoint in the upper arm and forearm). Each sensor sampled the x-position, y-position, z-position, yaw, roll, and elevation of the limb at 100 Hz over time and stored this information for further processing. A computer controlled target presentation and monitored upper limb movements in real time.

Targets and visual feedback regarding participant's task performance were projected onto the horizontal screen, positioned above a mirror that reflected the virtual image to the participant, creating a virtual reality environment. The starting circle and the target were projected together with a cursor that represented the participant's fingertip in the experimental space. This virtual reality environment was designed and calibrated to guarantee a true relationship between the cursor (virtual position) and the fingertip (real position). The cursor disappeared on movement initiation such that the participants had no online visual feedback information about hand position during the movement.

Each trial began when the participant positioned their fingertip in the displayed start location. The start location was positioned on the child's midline at a distance of approximately 24 cm from their trunk (see Fig. 2B). Once the child held the fingertip cursor in the start location for 2 s, one of three randomly-selected targets (located 12 cm away from the start) was shown (Fig. 2B). A straight-line connecting the start location and target center was also projected on the screen. Participants were instructed to reach for the target as quickly and as accurately as possible without making corrections. An audiovisual signal was used to signal the participant to initiate movement so they were aware of when they could start the movement, but they could start the movement any time after that; reaction time was not evaluated. After each movement, the trajectory of the hand was presented on the screen together with the points gained. Points were awarded for stopping close to the center of the target. The points earned were provided as motivation only.

2.4. Reaching measures

All kinematic data were low-pass filtered at 8 Hz (3rd order, dual pass Butterworth). Kinematic variables were processed and analyzed through routines developed in IGOR Pro (*WaveMetrics* Inc.). Movement start was determined as the time of the sample in which the resultant tangential velocity (x- and y-axes) of the hand marker exceeded 3% of peak hand velocity, whereas movement end was determined as the time of the sample in which the resultant velocity dropped and stayed below 5% of peak hand velocity. Visual inspection was performed on every single trial to ensure that movement start, peak hand velocity, and movement end were correctly determined.

End error is a measure of the distance between the center of the target and the fingertip at the end of the movement; this measure does not represent the direction of the error. Movement linearity is a measure of movement efficiency, as reaching movements that are planned and executed in a graceful and efficient manner tend to follow relatively straight hand paths [21]. Deviation from linearity was assessed as the minor axis of the movement hand path divided by the major axis [18,19,21]. Higher values on this measure of linearity represent greater levels of deviation and poorer movement efficiency. Peak hand velocity was the maximum value obtained from the hand position differentiation curve, and peak hand acceleration was the maximum point of the second derivative of hand position over time. Movement duration was calculated as the elapsed time from movement start to movement end. Distance covered was calculated as the linear distance between start and end locations of the hand. Elbow and shoulder excursion were calculated as the difference between final angular position and initial angular position from the elbow and shoulder angular displacement profiles, respectively.

Measures of movement variability (the standard deviation of performance around a participant's own mean) capture the precision, or lack thereof, of movement. Here variability was assessed by calculating the standard deviation of movement duration, distance, end error, deviation from linearity, shoulder and elbow excursion for each participant within each cell of the design. These measures were submitted to the regression analysis described below.

2.5. Statistical analysis

Reach difficulty was manipulated by varying target direction. It is well known that as the reach target varies from the 45-degree target to the 135-degree target, inter-joint coordination also varies, leaving predictable effects on movement performance [16–19]. To this point, elbow-to-shoulder excursion ratios vary strongly with target direction (see Fig. 4), such that elbow rotation dominates the reach to the 45-degree target, whereas the 90-degree and 135-degree targets demand increasingly greater contributions from the shoulder. While this well-known manipulation and its effects are interesting and will be examined, this study was focused on how reaching performance varied with group and reaching arm. To reveal these effects, we chose to submit each dependent variable to hierarchical regression analysis with target direction on the first level, group, arm and their interaction on the second level, and all other interactions involving target direction, group and arm on the third level (see Table 2). In this way, we can reveal the effects of group and arm after the variance associated with target direction is partialled from the pooled variance. To run regression on categorical variables like group and arm, group was dummy-coded as −.25 for the CTR group and +0.25 for the CwCP group, and arm was coded as −1 for the left/affected arm and +1 for the right/unaffected arm. Target direction was represented by the continuous variable target angle. R^2 is our measure of effect size of the model. Summarized data are presented as box plots. These box plots are overlaid with every data point. They show the median as a horizontal line. The box represents the interquartile range, the error bars represent 10th-90th percentile confidence intervals, and the black dots represent the 5th and 95th percentiles. The black line represents the slope of the best fit linear regression and gray lines represent the 95% confidence interval for this fit.

One assumption that needs to be satisfied for linear regression is that the predictor variable is linearly related to the dependent variable. We tested whether each dependent variable was better modeled by a linear, quadratic or inverse relationship. The linear model always described the strongest relationship between variables. We tested the assumption for normality by submitting the distributions for each dependent measure from each group to the Shapiro-Wilk test of normality. Not surprisingly, measures of timing and error showed skewed distributions. This is not uncommon in research with clinical populations. The strategy we adopted was to submit median values, not means, to analysis as median values better represent central tendency in skewed distributions.

3. Results

Fig. 3 shows the hand-paths of one representative child from each group reaching toward the 90-degree target direction. Trajectories of the CTR child are straighter than those performed by the child with CP. It is noticeable that the affected arm presented a greater level of trajectory curvature in comparison to the unaffected arm.

3.1. Movement duration

Whereas target direction alone (Model 1) accounted for a significant percentage of the variance in movement duration [$R^2 = 4.4\%$, $F(1,106) = 4.93$, $p = .029$], the best model (Model 2) included group, arm and their interaction and accounted for an additional 16.9% of the variance in movement duration, $R^2 = 23.1\%$, $F(4,103) = 7.37$, $p < .001$. Model 3 including the remaining interaction terms, accounts for only an additional 0.8% of the variance, $p = .807$. Target direction was positively correlated with movement duration $pr = .231$, $t(103) = 2.41$, $p = .018$, such that movement duration increased significantly as the target angle increased. Movement duration was significantly greater for the CwCP group (M ± SEM: 0.732 ± 0.022 s) than the control group (0.597 ± 0.022 s), $pr = .386$, $t(103) = 4.76$, $p < .001$, and movement duration was significantly greater for the left or affected arm (0.692 ± 0.022 s) than for the right or unaffected arm (0.627 ± 0.022 s), $pr = -0.207$, $t(103) = -2.15$, $p = .034$. There was no group by arm interaction ($pr = -0.07$, *n.s.*) and no other significant interaction (all ps > .36). Although the CwCP group moved more slowly than the control group overall, the

Table 2
Models tested in hierarchical regression analysis.

Model	Variables Entered
1	Target Direction
2	Target Direction, Group, Arm, Group x Arm
3	Target Direction, Group, Arm, Group x Arm, Target Direction x Arm, Group x Target Direction, Group x Arm x Target Direction

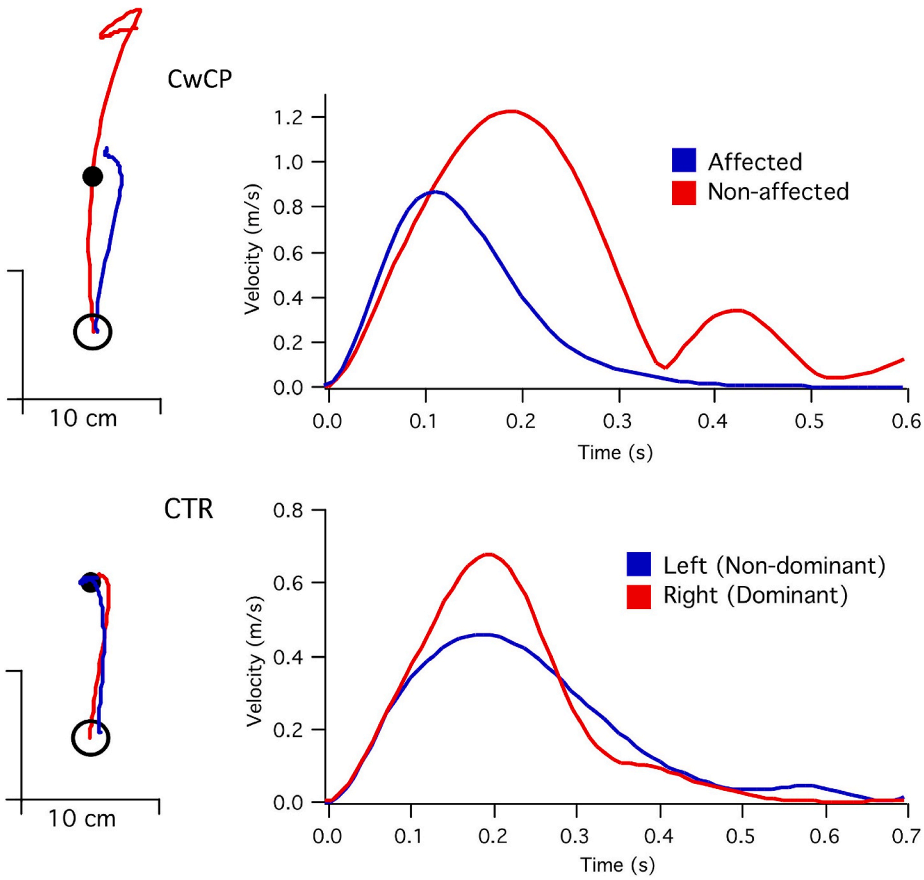

Fig. 3. Hand paths and hand velocity profiles of reaching movements made toward 90° target direction for representative participants for each group (top) unaffected and affected limbs of CwCP, and (bottom) right and left arms of CTR.

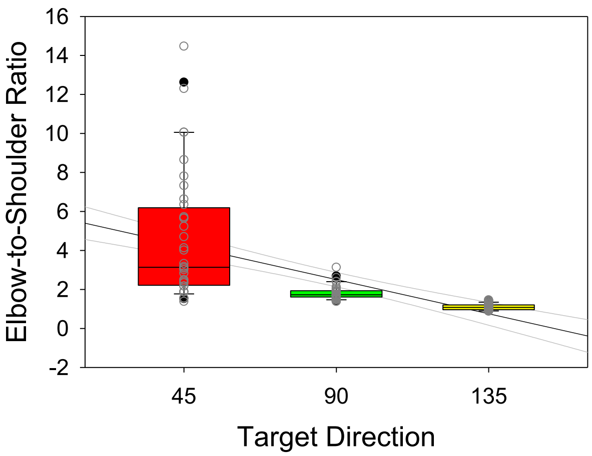

Fig. 4. Elbow-shoulder ratio as a function of target direction. These box plots are overlaid with every data point, shown as open gray circles. The box plots show the median as a horizontal line. The box represents the interquartile range, the error bars represent 10th-90th percentile confidence intervals, and the black dots represent the 5th and 95th percentiles. The black line represents the slope of the best fit linear regression and gray lines represent the 95% confidence interval for this fit.

difference between their affected and unaffected arm was not any greater than the difference between the left and right arm in control children.

3.2. Movement distance

Whereas target direction alone (Model 1) accounted for a significant percentage of the variance in movement distance, $R^2 = 7.9\%$, $F(1,106) = 9.11$, $p = .003$, the best model, Model 2, included group, arm and their interaction and accounted for an additional 9.1% of the variance in movement distance $R^2 = 17.0\%$, $F(4,103) = 5.28$, $p = .001$. Model 3 accounted for only 1.0% of the variance, $p = .734$. Target direction was negatively correlated with movement distance $pr = -0.295$, $t(103) = -3.13$, $p < .001$, such that movement distance decreased significantly as the target angle increased. Movement distance was significantly greater for the CwCP group (0.143 ± 0.005 m) than the control group (0.123 ± 0.005 m), $pr = .284$, $t(103) = 3.01$, $p = .003$. There was no significant effect of arm ($pr = -0.146$, $p = .138$) or group by arm interaction ($pr = -0.07$, *n.s.*) and no other significant interaction (all *ps* > .36). The CwCP group moved further than the control group overall.

3.3. Peak hand acceleration and peak hand velocity

Both peak hand acceleration and peak hand velocity varied only with target direction. Target direction accounted for 22.1% of the variance in peak hand acceleration, $F(1,106) = 30.01$, $p < .001$, but this was the only model that was significant (other *ps* > .11). Likewise, target direction accounted for 11.0% of the variance in peak hand velocity, $F(1,106) = 13.04$, $p < .001$, and models including other predictors did not do significantly better (*ps* > .11). Both peak hand acceleration ($pr = -0.470$) and peak hand velocity ($pr = -0.331$) were negatively associated with target direction such that peak hand acceleration and peak hand velocity decreased as target angle increased. This effect did not interact with group or arm.

3.4. End error

Model 1 did not account for a significant percentage of the variance, $R^2 = 2.0\%$, $p = .144$. The best model, Model 2, included group, arm and their interaction and accounted for an additional 9.4% of the variance in movement duration [$R^2 = 11.4\%$, $F(4,103) = 3.31$, $p = .014$]. Model 3 accounted for only 1.6% of the variance, $p = .597$. End error varied significantly with group, $pr = .288$, $t(103) = 3.05$, $p = .005$, such that end error was greater for the CwCP group (0.046 ± 0.004 m) than the control group (0.030 ± 0.004 m). There were no other factors or interactions that accounted the variance in end-error.

3.5. Deviation from movement linearity

Target direction alone (Model 1) accounted for a significant percentage of the variance, $R^2 = 20.0\%$, $F(1,106) = 26.53$, $p < .001$. Adding group, arm and their interaction accounted for an additional 26.8% of the variance, $F(1,103) = 17.30$, $p < .001$. Finally, adding the remaining interaction terms also accounted for a significant additional 4.7% of the variance, and represented the best model of the data, $R^2 = 51.5\%$, $F(7, 100) = 15.18$, $p < .001$. An examination of the coefficients revealed that deviation from linearity increased with increasing target angle, $pr = .541$, $t(100) = 6.43$, $p < .001$. This analysis also revealed an interaction of arm and target direction, $pr = -0.353$, $t(100) = -2.02$, $p = .046$ (see Fig. 5), and an interaction of group and target direction, $pr = .403$, $t(100) = 2.00$, $p = .049$ (see

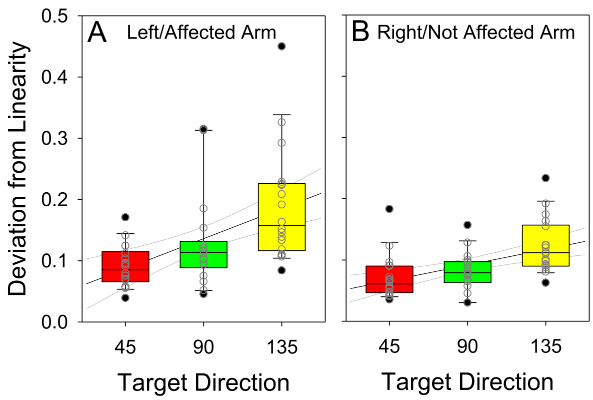

Fig. 5. Deviation from linearity as a function of arm and target direction. Panel A shows the left/affected arm and panel B shows the right/not-affected arm. This analysis revealed an interaction of arm and target direction, $pr = -0.353$, $t(100) = -2.02$, $p = .046$ such that the left arm of control children and the affected arm of children with CP show greater deviation as a function of target direction than the right/not-affected arm. These box plots are overlaid with every data point, shown as open gray circles. The box plots show the median as a horizontal line. The box represents the interquartile range, the error bars represent 10th-90th percentile confidence intervals, and the black dots represent the 5th and 95th percentiles. The black line represents the slope of the best fit linear regression and gray lines represent the 95% confidence interval for this fit.

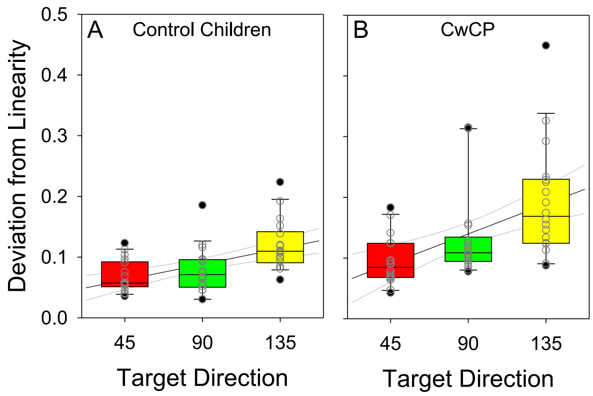

Fig. 6. Deviation from linearity as a function of group and target direction. Panel A shows control group performance and panel B shows the performance by children with cerebral palsy (CwCP). The children with CP show greater deviation as a function of target direction than CTR children, $pr = .403$, $t(100) = 2.00$, $p = .049$. These box plots are overlaid with every data point, shown as open gray circles. The box plots show the median as a horizontal line. The box represents the interquartile range, the error bars represent 10th-90th percentile confidence intervals, and the black dots represent the 5th and 95th percentiles. The black line represents the slope of the best fit linear regression and gray lines represent the 95% confidence interval for this fit.

Fig. 6). There was no interaction of group and arm (p = .666), and no three-way interaction of group, target direction, and arm ($p =$ .199).

An examination of the target direction by arm interaction shows that deviation from linearity is greater for the left or affected arm (see Fig. 5A) than the right or non-affected arm (see Fig. 5B), but that this difference is larger for the 90-degree and 135-degree targets than for the 45-degree targets. The group by target direction interaction shows that the CwCP (see Fig. 6B), group performed movements with greater deviation from linearity than the control group, but that this relationship is stronger for the 90-degree and 135-degree targets than for the 45-degree targets (see Fig. 6A).

3.6. Shoulder and elbow excursion

To address potential differences in interjoint coordination, we examined the effect of the reaching task on elbow and shoulder angular excursion. Analysis of shoulder excursion revealed that target direction (see Fig. 7B) alone accounted for 68.4% of the variance in shoulder excursion, $F(1,106) = 229.69$, $p < .001$. The best model, Model 2 (see Table 2), included group, arm and their interaction and accounted for an additional 3.5% of the variance in movement duration [$R^2 = 71.9\%$, $F(3,103) = 65.97$, $p < .001$]. Model 3 (see Table 2) accounted for only 0.6% of the variance, p = .541. Shoulder excursion varied significantly with target direction, $pr = .842$, $t(103) = 15.84$, $p < .001$, such that shoulder involvement increased reliably with target angle, as expected. Shoulder involvement also varied significantly with group, $pr = .327$, t(103) = 3.51, p = .001, such that shoulder rotation was greater for the CwCP group than in the control group (see Fig. 7A). There were no other factors or interactions that accounted for variance in shoulder rotation.

Analysis of elbow excursion revealed that target direction alone accounted for 8.8% of the variance in elbow excursion, $F(1,106) =$ 10.20, $p = .002$. The best model, Model 2, included group, arm and their interaction and accounted for an additional 14.8% of the variance in movement duration [$R^2 = 23.5\%$, $F(4,103) = 7.93$, $p < .001$]. Model 3 accounted for only an additional 0.4% of the variance, $p = .924$. Elbow excursion varied significantly with target direction (see Fig. 8B), $pr = -0.321$, $t(103) = -3.44$, $p = .001$, such that elbow involvement also increased reliably between the 45-degree and 90-degree targets, but did not differ between the 90-degree and 135-degree targets. Elbow involvement also varied significantly with group, $pr = -380$, t(103) = −4.17, p < .001, such that elbow rotation was greater for the CwCP group than the control group (see Fig. 8A). There were no other factors or interactions that accounted the variance in elbow rotation.

3.7. Movement precision

Movement duration precision was best captured by model 2, which accounted for 12.8% of the variance in timing precision, F(3,103) = 5.05, p = .006. An examination of the coefficients revealed that the factor driving this effect was group, pr = .348, t(103) = 3.77, p < .001, and that the CwCP had significantly greater timing precision than the CTR group. There were no other variables or interactions that accounted for this data.

Although target direction alone captured 14.3% of the variance in movement distance precision, Model 2 captured variation in this measure best, $R^2 = 26.1\%$, $F(4,103) = 9.10$, $p < .001$. Target direction varied negatively with this measure, $pr = -0.379$, $t(103) = -4.47$, $p < .001$, such that participants were the least precise at reproducing distance when moving to the 45-degree target direction and more precision for the 135-degree target direction. There was also a group effect, $pr = .343$, $t(103) = 4.07$, $p < .001$, such that the CwCP group was less precise in movement distance production than the CTR group.

The end error precision was also best captured by Model 2 (see Table 2), $R^2 = 24.6\%$, $F(4,103) = 8.40$, $p < .001$. Target direction

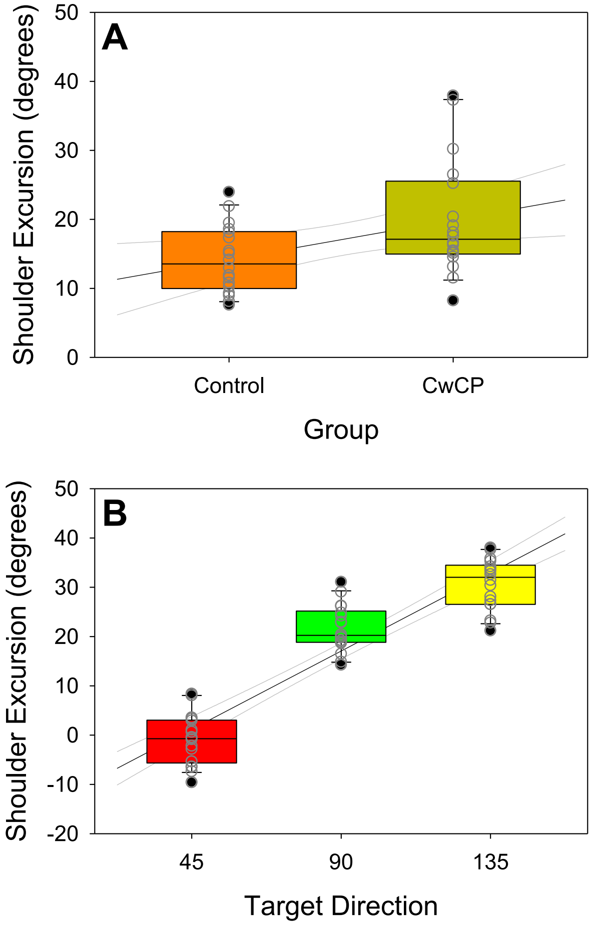

Fig. 7. Shoulder excursion as a function of group (Panel A) and target direction (Panel B). Overall, children with CP show significantly larger shoulder excursions than the control children, *pr* = .327, t(103) = 3.51, p = .001. Shoulder excursion increases significantly with target direction, *pr* = .842, *t*(103) = 15.84, *p* < .001. These box plots are overlaid with every data point, shown as open gray circles. The box plots show the median as a horizontal line. The box represents the interquartile range, the error bars represent 10th-90th percentile confidence intervals, and the black dots represent the 5th and 95th percentiles. The black line represents the slope of the best fit linear regression and gray lines represent the 95% confidence interval for this fit.

varied negatively with this measure, *pr* = −0.311, *t*(103) = −3.63, *p* < .001, such that participants were less precise when moving to the 45-degree target direction and more precise for the 135-degree target direction. There was also a group effect, *pr* = .381, *t*(103) = 4.54, *p* < .001, such that the CwCP group produced end-error values that were less precise than the CTR group.

Target direction alone captured 22.3% of the variance in deviation from linearity variability data, F(1, 106) = 30.40, p < .001, and Model 2 accounted for an additional 7.0% of variance, F(4, 103) = 10.65, p < .001. Target direction varied positively with curvature variability, such that participants' deviation from linearity was more variable when reaching for the 135° target than the 45° target, pr = .49, t(103) = 5.70, p < .001. There was also a group effect, pr = .26, t(103) = 2.68, p = .009, such that the CwCP group's linearity was more variable than the CTR group.

Although target direction alone captured 15.0% of the variance in shoulder excursion variability, F(1,106) = 18.69, p < .001, this measure was also best captured by Model 2, R^2 = 26.9%, F(4, 103) = 9.48, p < .001. Both target (*pr* = .41, t(103) = 4.60, p < .001) and group (pr = .37, t(103) = 4.02), p < .001) were significant such that shoulder excursion variability was greater for 135-degree target direction than for 45-degree target direction, and variability was greater for the CwCP group than for the CTR group.

Finally, elbow excursion variance was captured only by Model 2, R2 = 13.7%, F(4, 103) = 4.07, p = .004. Group was the only factor that varied with elbow excursion variability, pr = .36, t(103) = 3.88, p < .001, such that elbow excursion variability was greater for the CwCP group than the CTR group.

Overall, these analyses of movement precision show that, consistent with previously reported research [22,23], precision varied with target direction. Perhaps not surprisingly, precision varied by group such that the CwCP group performed reaching movements more variably than the CTR group across all measures.

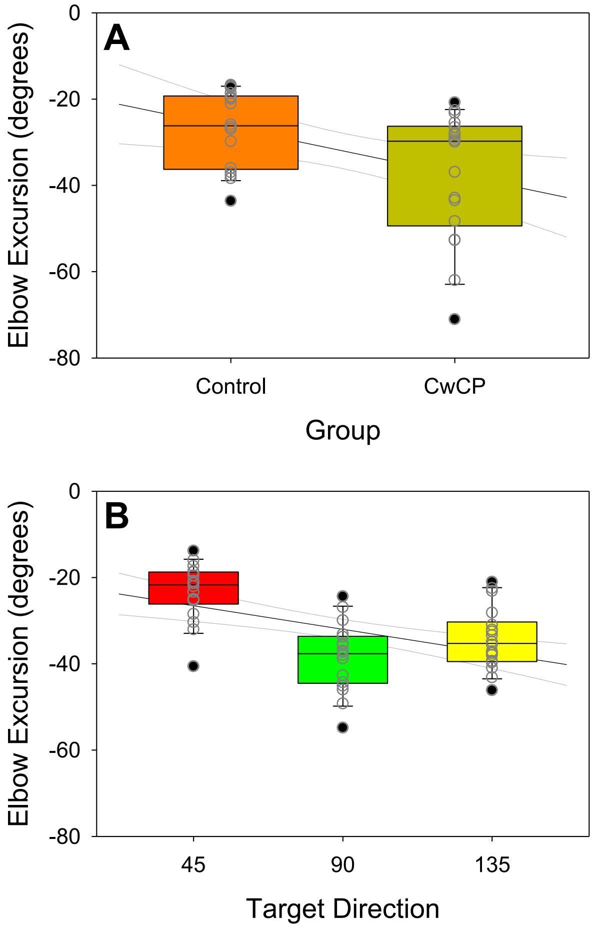

Fig. 8. Elbow excursion as a function of group (Panel A) and target direction (Panel B). Overall, children with CP show significantly larger elbow excursions than the control children, $pr = -380$, $t(103) = -4.17$, $p < .001$. Elbow excursion increases significantly with target direction, $pr = -0.321$, $t(103) = -3.44$, $p = .001$. These box plots are overlaid with every data point, shown as open gray circles. The box plots show the median as a horizontal line. The box represents the interquartile range, the error bars represent 10th-90th percentile confidence intervals, and the black dots represent the 5th and 95th percentiles. The black line represents the slope of the best fit linear regression and gray lines represent the 95% confidence interval for this fit.

4. Discussion

We asked children with unilateral cerebral palsy (CP) and typically-developing control (CTR) children to reach for three targets that varied in direction with both their left/affected and right/not-affected hands. Participants were instructed to reach for the target as quickly and as accurately as possible without making corrections and they were given points that rewarded accuracy. We measured movement time, distance, peak velocity and acceleration, and hand-path linearity. We measured the contributions of shoulder and elbow rotation to the movement and analyzed the variability of the movement path and endpoint around each participant's own mean performance. We found that children with CP (CwCP) made reaches that covered greater distance and took more time, that the shoulder and elbow excursion greater, and that their movements showed greater deviation from linearity than the movements performed by CTR children. Children with CP were more variable than CTR children on every measure except movement duration.

In this study, children with cerebral palsy (CwCP) showed reduced ability to perform reaching movements in comparison to CTR children [9]. Relatively few studies have described reaching movements in children with CP. In addition, the heterogeneity of tasks, contexts and measures of kinematic analysis can make direct comparisons difficult. Most of these studies consider movement duration, peak velocity and hand-path trajectory as dependent variables [4,14,15,24,25]. In this study, CwCP produced movements that were greater in distance, duration, and deviation from linearity compared to CTR children. These results are similar to other reports in the literature [4,15,24,25]. While our measures were more sensitive at the group level, Ricken et al. [26], Ronnqvist et al. [27] and Van Der Heide et al. [28] analyzed reaching movements in children with CP and reported longer movement duration in the affected arm than in the unaffected arm, in general agreement with our findings. When analyzing the preferred side of control children and CP children, Van Der Heide [28] found that the unaffected arm of CwCP produced movements with longer duration than CTR children, a result that we did not find, but the Van Der Heide study did not take children's handedness into consideration. According to Annett et al. [7], another important factor is that for the non-preferred or affected limb, the level of movement difficulty may demand greater feedback control, generating a longer movement time in comparison to the preferred limb. In the current study, feedback-based corrections were prohibited by removing online feedback, perhaps exacerbating the effect of this factor and revealing differences between groups.

In addition to taking more time to perform, CwCP covered a greater distance, showed greater movement curvature (deviation from linearity), larger shoulder and elbow excursions, and consequently had greater end-point error than CTR children. As expected [18,19,21], deviation from linearity was greater for the left/affected arm than for the right/non-affected arm. It is possible that this may be explained by the notion that CwCP failed to adapt with practice to the reduced friction environment and this impaired CwCP's already-precarious braking capability. This explanation may also account for increases in movement variability on almost all measures. Why were CwCP less able to adapt to a frictionless environment than CTR children? The finding that many of the differences in performance between CwCP and CTR children varied with target direction may provide answers to this question.

The pattern of increased shoulder and elbow rotation in the CwCP group represents a coordination pattern that is significantly different from the pattern used by control children. This pattern may represent a greater reliance in the CwCP group on proximal muscular control systems than in CTR children. This control scheme is disadvantageous because additional shoulder rotation will be accompanied by increased need to counteract interaction torques, an action that may be underserved in a disorder that weakens distal control systems that originate in the cortex (cortical spinal system), and may lead to greater reactive elbow rotation, greater movement distance covered than necessary, and larger spatial errors produced despite using more time to produce the movement.

One possibility is that CwCP have difficulty coordinating elbow and shoulder muscle activation due to injury to the primary motor cortex and the cortical spinal tract (CST). The finding that target directions demanding greater shoulder rotation (90-degree and 135-degree targets) also led to greater elbow rotation and deviation from linearity suggests that CwCP may have a decreased ability to plan for and compensate for the interaction torques invoked by additional shoulder rotation. These compensation processes may rely on a damaged cortical system. We know that compensation for interaction torques depends greatly on somatosensory (touch and proprioceptive) processing [29,30]. This sensory processeing may be compromised in CwCP due to changes in cortical processing affecting primary motor and primary somatosensory cortices that lie in close proximity to one another [3,11]. Research in chronic stroke survivors shows that patients' ability to exert control over the excitability of the spinal motor neuron pool of and improve reaching skill in the stroke-affected limb with training depends on the viability of ipsilateral cortical spinal projections to the affected limb [31]. One major alternative possibility, that proximal (shoulder) control could be mediated by the reticulospinal tract in the absence of cortical-spinal input, was ruled out by Hill and Dewald's [25] finding that experimental shoulder-loading failed to induce hypermetria in their CwCP participants, suggesting that synergies associated with reticulospinal inputs do not contribute to control of the affected limb. Altogether, this evidence suggests that CwCP may have a decreased ability to plan for, sense, and compensate for the forces affecting limb coordination during movement and that this deficit may be attributable to changes in the viability of cortical sensorimotor processing and cortical-spinal projections.

Although more research is needed to test this hypothesis directly, the notion that CP children are more vulnerable to deficits of movement planning, execution, and feedback-related correction is important in a physical therapy context, as children with CP tend to use the affected arm less frequently, generating an asymmetry that may be amplified because of the "non-use" effect. Indeed, Qui et al. [15] reported that feedback-related control can be significantly improved both in clinic and in activities of daily living with physical therapy training.

The strengths of the study lie in our task choice. The task was chosen with the knowledge that varying target direction changes the difficulty of limb coordination in a systematic way [18,19,21]. We age- and gender-matched our groups. Our CwCP participants were all affected by CP unilaterally, and our control participants were all strong right-handers, strengthening the opportunity to find differences between CwCP and CTR children. One of the limitations of the study is that the sample size is relatively low. In a future study, hand and/or wrist motion and multiplanar repetitive motions can be added.

Our finding that CwCP use a multijoint coordination pattern that is significantly different from the pattern used by control children suggests that CwCP may benefit from techniques that encourage practice and learning of multijoint coordination patterns. For example, exercises that force CwCP to practice reaching across the body or into workspaces that demand large joint rotations may lead to learning of direct or alternative strategies for compensating for interaction torques. Techniques that enhance the somatosensory information needed to adopt compensatory strategies, for example, skin taping techniques that enhance somatosensory signals arising from movement, may also assist with multijoint coordination in the affected limb. Recent research suggests that elastic taping benefits range of motion in the affected limb [32]. The effectiveness of these options will need to be determined.

Author contribution statement

Leia B Bagesteiro: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Tamires L Tellini: Performed the experiments; Analyzed and interpreted the data.

Liana E Brown: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

The data that has been used is confidential.

Declaration of interest's statement

The authors declare no competing interests.

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References

[1] J. Lambert, C. Bard, Acquisition of visuomanual skills and improvement of information processing capacities in 6 to 10 year old children performing a 2D pointing task, Neurosci. Lett. 377 (2005) 1–6.
[2] Y. Chen, et al., Use of virtual reality to improve upper-extremity control in children with cerebral palsy: a single-subject design, Phys. Ther. 87 (2007) 1441–1457.
[3] S.N. Kukke, L.A. Curatalo, A.C. de Campos, M. Hallett, K.E. Alter, D.L. Damiano, Coordination of reach-to-grasp kinematics in individuals with childhood-onset dystonia due to hemiplegic cerebral palsy, IEEE Trans. Neural Syst. Rehabil. Eng. 24 (5) (2016) 582–590, https://doi.org/10.1109/TNSRE.2015.2458293.
[4] E. Ramos, M.P. Latash, E.A. Hurvitz, S.H. Brown, Quantification of upper extremity function using kinematic analysis, Arch. Phys. Med. Rehabil. 78 (1997) 491–496.
[5] J. Barral, B. Debû, Hand and gender differences in the organization of aiming in 5-year-old children, Neuropsychologia 40 (2) (2002) 152–161, https://doi.org/10.1016/s0028-3932(01)00080-x.
[6] M. Petrarca, G. Zanelli, F. Patanè, F. Frascarelli, P. Cappa, E. Castelli, Reach-to-grasp interjoint coordination for moving objects in children with hemiplegia, J. Rehabil. Med. 41 (2009) 995–1002.
[7] J. Annett, M. Annett, P.T.W. Hudson, A. Turner, The control of movement in the preferred and non preferred hands, Q. J. Exp. Psychol. 31A (1979) 641–652.
[8] J.J. Chang, T.I. Wu, W.L. Wu, F.C. Su, Kinematical measure for spastic reaching in children with cerebral palsy, Clin. BioMech. 20 (4) (2005) 381–388, https://doi.org/10.1016/j.clinbiomech.2004.11.015.
[9] A.H. Mackey, S.E. Walt, N.S. Stott, Deficits in upper-limb task performance in children with hemiplegic cerebral palsy as defined by 3-dimensional kinematics, Arch. Phys. Med. Rehabil. 87 (2006) 207–215.
[10] E.A. Aboelnasr, F.A. Hegazy, H.A. Altaway, Kinematic characteristics of reaching in children with hemiplegic cerebral palsy: a comparative study, Brain Inj. 31 (2017) 83–89, https://doi.org/10.1080/02699052.2016.1210230.
[11] S. Saaveda, A. Joshi, M. Wollacott, P. van Donkelaar, Eye hand coordination in children with cerebral palsy, Exp. Brain Res. 192 (2009) 155–165, https://doi.org/10.1007/s00221-008-1549-8.
[12] A. Losse, et al., Clumsiness in children – do they grow out of it? A 10-year study, Dev. Med. Child Neurol. 33 (1991) 55–68.
[13] L. Hay, et al., Resolving power of the perceptual and sensory motor systems in 6 to 10 year-old children, J. Mot. Behav. 26 (1984) 36–42.
[14] G.P. Aylward, Neurodevelopmental outcomes of infants born prematurely. Review, J. Dev. Behav. Pediatr. 26 (6) (2005) 427–440.
[15] Q. Qui, S. Adamovich, S. Saleh, I. Lafond, A.S. Merians, G.G. Fluet, A comparison of motor adaptations to robotically facilitated upper extremity task practice demonstrated by children with cerebral palsy and adults with stroke, IEEE Int. Conf. Rehab. Robotics (2011).
[16] R.L. Sainburg, M.F. Ghilardi, H. Poizner, C. Ghez, Control of limb dynamics in normal subjects and patients without proprioception, J. Neurophysiol. 73 (1995) 820–835.
[17] R.L. Sainburg, C. Ghez, D. Kalakanis, Intersegmental dynamics are controlled by sequential anticipatory, error correction, and postural mechanisms, J. Neurophysiol. 81 (3) (1999) 1045–1056, https://doi.org/10.1152/jn.1999.81.3.1045.
[18] L.B. Bagesteiro, R.L. Sainburg, Handedness: dominant arm advantages in control of limb dynamics, J. Neurophysiol. 88 (5) (2002) 2408–2421.
[19] L.B. Bagesteiro, R.B. Balthazar, C. Hughes, Movement kinematics and interjoint coordination are influenced by target location and arm in 6-year-old children, Front. Hum. Neurosci. 14 (2020), 554378, https://doi.org/10.3389/fnhum.2020.554378.
[20] L.B. Bagesteiro, K.O. Lima, J. Wang, Interlimb differences in visuomotor and dynamic adaptation during targeted reaching in children, Hum. Mov. Sci. 77 (2021), 102788, https://doi.org/10.1016/j.humov.2021.102788.
[21] R.L. Sainburg, D. Kalakanis, Differences in control of limb dynamics during dominant and nondominant arm reaching, J. Neurophysiol. 83 (5) (2000) 2661–2675.
[22] J. Gordon, M.F. Ghilardi, C. Ghez, Accuracy of planar reaching movements. 1. Independence of direction and extent variability, Exp. Brain Res. 99 (1994) 97–111.
[23] J. Gordon, M.F. Ghilardi, S.E. Cooper, C. Ghez, Accuracy of planar reaching movements. 2. Systematic extent errors arising from inertial anisotropy, Exp. Brain Res. 99 (1994) 112–130.
[24] A.M. Kuczynski, A. Kirton, J.A. Semrau, S.P. Dukelow, Bilateral reaching deficits after unilateral perinatal ischemic stroke: a population-based case-control study, J. NeuroEng. Rehabil. 15 (2018) 77, https://doi.org/10.1186/s12984-018-0420-9.
[25] N.M. Hill, J.P.A. DeWald, The upper extremity flexion synergy is minimally expressed in young individuals with unilateral cerebral palsy following early brain injury, Front. Hum. Neurosci. 14 (2020), 590198, https://doi.org/10.3389/fnhum.2020.590198.
[26] A. Ricken, S.J. Bennett, G.J. Savelsbergh, Coordination of reaching in children with spastic hemiparetic cerebral palsy under different task demands, Mot. Control 9 (2005) 357–371.
[27] L. Ronnqvist, B. Rosblad, Kinematic analysis of unimanual reaching and grasping movements in children with hemiplegic cerebral palsy, Clin. BioMech. 22 (2007) 165–175.
[28] J.C. Van Der Heide, J.M. Fock, B. Otten, E. Stremmelaar, M. Hadders-Algra, Kinematic characteristics of reaching movements in preterm children with cerebral palsy, Pediatr. Res. 57 (2005) 883–889.
[29] R.L. Sainburg, H. Poizner, C. Ghez, Loss of proprioception produces deficits in interjoint coordination, J. Neurophysiol. 70 (1993) 2136–2147.
[30] A.J. Bastian, T.A. Martin, J.G. Keating, W.T. Thach, Cerebellar ataxia: abnormal control of interaction torques across multiple joints, J. Neurophysiol. 76 (1) (1996) 492–509, https://doi.org/10.1152/jn.1996.76.1.492.
[31] U. Hammerbeck, S.F. Tyson, P. Samraj, K. Hollands, J.W. Krakauer, J. Rothwell, The Strength of the corticospinal tract not the reticulospinal tract determines upper-limb impairment level and capacity for skill-acquisition in the sub-acute post-stroke period, Neurorehabilitation Neural Repair 35 (9) (2021) 812–822, https://doi.org/10.1177/15459683211028243.
[32] E. Ackibas, D. Tarakci, M. Budak, Comparison of the effects of Kinesio tape and neuromuscular electrical stimulation on hand extensors in children with cerebral palsy, Int. J. Ther. Rehabil. 27 (7) (2020) 1–12, https://doi.org/10.12968/ijtr.2019.0053.