Object release under varying task constraints in children with hemiplegic cerebral palsy

Andrew M Gordon* PhD, Department of Biobehavioral Sciences, Teachers College, Columbia University, New York; Sarah R Lewis, Department of Biobehavioral Sciences, Teachers College, Columbia University, New York, USA; Ann-Christin Eliasson, Department of Woman and Child Health, Karolinska Institute, Stockholm, Sweden. Susan V Duff, Shriners Hospital for Children, Philadelphia, USA.

*Correspondence to first author at Department of Biobehavioral Sciences, Box 199, Teachers College, Columbia University, 525 West 120th Street, New York, NY 10027, USA. E-mail: ag275@columbia.edu

Considerable attention has been given in recent years to fingertip force coordination during grasping and lifting small objects in children with cerebral palsy (CP). However, little is known about the children’s ability to replace and release an object from grasp. The present study examined the coordination of fingertip forces during replacement and release of an object from grasp under varying task constraints in the involved hand of 15 children (10 males, five females, age range 7 to 14 years) with hemiplegic CP and in the non-dominant hand of 15 age-matched, typically-developing children (seven males, eight females). Participants released an object, instrumented with force transducers and held with a precision grip, onto a stable surface and onto an unstable surface (requiring higher accuracy) at self-paced and fast-as-possible speeds. Temporal and force measures were recorded and the dependent measures were tested using analyses of variance. Results showed that force coordination was impaired in children with hemiplegia, resulting in prolonged and uncoordinated replacement and release of the object (p<0.05). Differences between controls and children with hemiplegia were greater when speed and accuracy constraints were imposed (i.e. task performance was affected by these constraints to a greater extent in the children with CP, p<0.05). Impairments in temporal coordination of object release were also observed in the non-involved hand under all conditions (p<0.05). These results provide additional information about impaired hand function in children with hemiplegic CP. Clinical implications of these findings are discussed.

Children with hemiplegic cerebral palsy (CP) have difficulty using their involved hand for skilled, manipulatory activities. The clinical features of their hand impairment include slowness, weakness, uncoordinated movements, incomplete finger individuation, and spasticity (Twitchell 1958, Brown et al. 1987, Uvebrant 1988). Furthermore, in approximately 50% of this population tactile sensibility is impaired, which also affects hand use (Uvebrant 1988, Cooper et al. 1995, Gordon and Duff 1999b, Krumlinde-Sundholm and Eliasson 2002).

In the last decade, considerable attention has been given to the development of prehensile force control during grasping and lifting objects in both normally developing children (Forsberg et al. 1991, 1992, 1995; Gordon et al. 1992, 1994; Eliasson et al. 1995a; Peré and Dugas 1999; see Gordon 2001 for review) and children with CP (Eliasson et al. 1991, 1992, 1995b; Steenbergen et al. 1998; Forsberg et al. 1999; Gordon and Duff 1999a,b; Gordon et al. 1999; Kuhntz-Buschbeck et al. 2000). These studies have begun to elucidate mechanisms underlying normal motor control in the performance of this task, as well as the neural basis of impairments in children with CP. Specifically, children with CP exhibit impairments in fingertip force control and timing during object manipulation. Furthermore, they show a deficit in anticipatory control of fingertip force development based on the object’s physical properties (Eliasson et al. 1992, 1995b; Gordon and Duff 1999a; Gordon and Duff 1999b).

Considerably less attention, however, has been given to the mechanism underlying the release of a grasped object. The ability to place an object onto a surface accurately and release it from grasp is functionally as important as the ability to grasp and lift it. Object release demands precise coordination of fingertip forces and timing for predicting accurate object placement and to ensure that the object does not drop or hit the support surface too forcefully (Gordon 1998, Eliasson and Gordon 2000, Lewis et al. 2002). In a recent study of force coordination during object release, children with hemiplegic CP demonstrated an impaired ability to replace and release objects smoothly (Eliasson and Gordon 2000). Specifically, there was an abrupt replacement of the object onto the table surface and the force coordination was impaired resulting in a prolonged and uncoordinated release of the grasp. In that study, however, children were only required to replace the object on a stable surface at their preferred pace. In our earlier work on typically developing children (Lewis et al. 2002) and individuals with Parkinson’s disease (Gordon 1998), the force coordination patterns differed depending on the speed and accuracy constraints that were imposed. For example, for typically-developing children, object replacement with the non-dominant hand took longer than with the dominant hand and force coordination differed between the hands, mainly when speed and accuracy constraints were introduced.

The aim of the present study was to examine further the coordination of grip and load forces during the replacement and release of an object from grasp in children with hemiplegic CP. We tested the hypothesis that differences in object replacement and release between typically-developing children and children with hemiplegia would be greater when speed and accuracy were required. Furthermore, we investigated whether there were impairments in the coordination of this task in the non-involved extremity.
Methods

Participants

Fifteen children with hemiplegic CP (10 males, five females, age range 7 to 14 years) and 15 age-matched, typically-developing control children (seven males, eight females) selected from schools and clinics in the New York City metropolitan area, participated in the study. This age group was selected because typically-developing children approximate the grasping behavior of adults by age 6 to 8 years (Forssberg et al. 1991, 1992, 1995; Gordon et al. 1992). All participants could grasp and lift the grip apparatus using a precision grip or lateral pinch pattern, follow task directions, and were cognitively unimpaired (scored within 2SDs on the Kaufman Brief Intelligence Test (Kaufman and Kaufman 1990). Diagnosis of hemiplegia (lack of obvious sensory and motor impairments on one side of the body) was made by the referring clinicians and by the investigators’ clinical assessment. Children were excluded if they had any orthopedic anomalies that would interfere with task performance, uncontrolled seizures, or significant visual deficits. All typically-developing children were right hand dominant as assessed by parent/child report and confirmed using the Edinburgh Handedness Inventory (Oldfield 1971). Informed consent was obtained from all participating children and their parents. The study was approved by the

Figure 1: (a) Schematic diagram of grip instrument with (i) grip surfaces covering force transducers and (ii) an electromagnetic position sensor. (b) Schematic diagram of experimental set-up, including: (i) grip device lifted to (ii) horizontal bar which served as a vertical marker for lifting height; (iii) stable surface on which object was replaced, for normal conditions; (iv) unstable surface on which object was replaced for accuracy conditions; and (v) Polhemus position transmitter. (c) Grip force from index finger (ind) and thumb (t); grip force rate, load force, vertical position, and velocity for a representative trial with non-dominant hand during object release under low accuracy, self-paced conditions. Vertical lines indicate initiation of (T0) replacement or vertical displacement of object; (T1) object contact with table; (T2) release of one digit; and then (T3) release of opposing digit. Measured force parameters are indicated by arrows showing: (F1) peak velocity; (F2) velocity before object down (5mm); (F3) maximal grip force rate; (F4) grip force at initiation of replacement; and (F5) grip force at object down.
A custom-made grip apparatus was used to measure fingertip forces from two parallel contact surfaces, covered with grit sandpaper, 30mm in diameter and 45mm apart (see Fig. 1a). The contact surfaces covered force-torque sensors (Nano E/T transducer; ATI Industrial Automation, NC, USA) that measured the orthogonal force components (Fy and Fz, 0.025N and 0.05N resolution, respectively). The base of the object was 7.5×5cm. An electromagnetic position-angle sensor (Polhemus Fastrack, 0.75mm resolution; Colchester, VT, USA; Fig. 1a, ii) mounted on the apparatus measured its vertical position. The total weight of the apparatus was 265g.

**Results**

Overall, the task was completed successfully without dropping the apparatus in all cases for both groups of children when replacing it to the stable surface. When higher accuracy was required, the controls never dropped the object, whereas one child with hemiplegia dropped the object on one trial. Thus both groups of children were able to complete the task without significant problems. However, as described below, the manner in which it was completed differed considerably between the two groups of children.

**Temporal regulation of object release**

Figure 2 shows a representative trial of object replacement and release for the non-dominant hand of a healthy control child and the involved hand of a child with hemiplegia during the preferred-speed low- and high-accuracy conditions. Overall, the duration of this task (T0–T3) was longer for the child with hemiplegia. The control child replaced the object steadily, resulting in a brief replacement phase (T0–T1) in which the object was repositioned to the table. Following table contact, the grip and load forces decreased rapidly (T1–T2) until each digit was removed from the object in quick succession (T2–T3). In contrast, all three phases were
prolonged for the child with hemiplegia. Not surprisingly, the phases were longer for both children when replacing the object when greater accuracy was required.

Figure 3 shows that these findings were representative of the children we tested. The replacement (Fig. 3a) and release phases (Fig. 3b) and the duration between release of each digit (Fig. 3c) were longer for the children with hemiplegia across all conditions (i.e. there was a main effect, $p<0.005$, in all cases). There was also an increased coefficient of variation for the release phase duration ($p<0.05$) across all conditions.

COORDINATION OF REPLACEMENT AND RELEASE

Peak velocity during transport of the object to the table (Fig. 4a) and velocity just before table contact (Fig. 4b) were both lower for the children with hemiplegia across all conditions ($p<0.001$ in both cases). The velocity just before table contact was also more variable for the children with hemiplegia ($p<0.05$). During the release phase, the peak rate of grip force decrease was lower for the children with hemiplegia across all conditions ($p<0.001$; Fig. 4c). Interestingly, on average across all conditions, the peak rate of grip force decrease occurred approximately 100ms before table contact for the children with hemiplegia, whereas it occurred approximately 100ms after table contact for the control children ($p<0.05$; not shown).

During the static phase (Fig. 5a) when the object was held in the air, and at the onset of replacement (Fig. 5b), grip forces were similar for both groups of children in all conditions ($p>0.05$). However, the grip force at table contact (Fig. 5c) was higher for the controls in all conditions ($p<0.01$ in all cases). Thus while the forces in the static phase were not appreciably different in the two groups of children, the children with hemiplegia decreased their grip forces in anticipation of table contact to a greater extent than controls, by beginning the decrease earlier.

EFFECTS OF TASK CONSTRAINTS

The above results show that force coordination was impaired in the children with hemiplegia, resulting in a prolonged and uncoordinated replacement and release of the object. However, as described below, the differences in performance between the controls and children with hemiplegia varied, depending on the specific speed and accuracy constraints imposed.

When increased accuracy was required all participants slowed down, though the children with hemiplegia slowed down more than the controls. Figure 6 shows the amount of change (%) from the low accuracy, preferred-speed condition (see also high-accuracy condition in Fig. 2). The duration between release (Fig. 6c) of each digit was prolonged to a significantly greater extent (i.e. group x accuracy interaction, $p<0.05$) and there was a tendency for the replacement phase duration (Fig. 6a) to be longer and the velocity just before table contact (Fig. 6e) to be lower (group x accuracy interaction $p<0.09$ in both cases). Grip force at onset of replacement (see Fig. 5b) was greater for the controls when accuracy was

**Figure 2:** Grip force from index finger (ind) and thumb (t); grip force rate, load force, vertical position, and velocity for representative trials during object release for a control child and a child with hemiplegia during self-paced low and high-accuracy conditions.
required (group × accuracy interaction p<0.05).

When participants were required to increase their speed, the control children sped up the movement, and consequently the peak velocity during transport of the object to the table (Fig. 6d) and the velocity just before table contact (Fig. 6e) were increased. The children with hemiplegia sped up the replacement time and finger release difference when asked to perform the task quickly. While the release phase appeared to increase slightly (Fig. 6b) when speed was required, the mean increase was caused by only two children (13/15 children decreased their release phase duration). With increased speed, the peak velocity and the velocity just before table contact (Fig. 6d, 6e) were reduced to a greater extent for the children with hemiplegia than for the controls (group × speed interaction

![Figure 3: Mean (±SEM) duration of (a) replacement phase, (b) release phase, and (c) finger difference for non-dominant hand of controls and involved hand of children with hemiplegia for all conditions.](image)

![Figure 4: Mean (±SEM) of (a) peak velocity, (b) velocity just before table contact, and (c) peak rate of grip force decrease for non-dominant hand of controls and involved hand of children with hemiplegia for all conditions.](image)

![Figure 5: Mean (±SEM) grip force (a) during static phase, (b) at replacement onset, and (c) at table contact for non-dominant hand of controls and involved hand of children with hemiplegia for all conditions.](image)
Similarly, the peak rate of grip force increase to a greater extent for the controls (group×speed interaction p<0.05) when speed was required.

When both speed and accuracy were required, the differences were more pronounced for children with hemiplegia. The controls slightly reduced the replacement and release phase but they slightly increased the duration between finger release (Fig. 6a–c). Children with hemiplegia were slower for all three phases. During the fast, high-accuracy condition, the peak rate of grip force decrease (Fig. 6f) was greater for the controls than for the children with hemiplegia (group×speed×accuracy interaction p<0.05). There was a group×speed×accuracy interaction of the grip force at table contact (p<0.05).

OBJECT RELEASE IN NON-INVOLVED HAND

Figure 7 shows the duration of replacement (Fig. 7a), release time (Fig. 7b), and finger difference (Fig. 7c) for the non-involved hand of the children with hemiplegia and the non-dominant hand of the control children. Across all conditions, the replacement and release times were significantly greater for the children with hemiplegia (p<0.01). Finger difference time also tended to be longer for the children with hemiplegia (especially for the high-accuracy conditions), although the differences between groups did not reach statistical significance. Temporal and force coordination generally varied according to the speed and accuracy constraints in the same manner for both groups of children (i.e. there was no group×speed or group×accuracy interaction for any measured parameter).

Replacement time and the velocity before table contact were more variable for the children with hemiplegia across all conditions (p<0.05). There was a group×speed interaction for the replacement time, whereby the coefficient of variation was affected by speed to a greater extent for the children with hemiplegia (p<0.05).

Discussion

The results of the present study are in agreement with our
earlier findings that children with hemiplegic CP have an impaired ability to replace and release objects smoothly. Specifically, force coordination is impaired resulting in prolonged and uncoordinated replacement and release of the grasp. This study revealed that the differences between the controls and children with hemiplegia were greater when speed and accuracy constraints were imposed, with some parameters being affected to a greater extent when speed was required and others when accuracy was required. The non-involved hand also displayed impairments in the temporal coordination of object release. These results provide additional information about impaired hand function in children with hemiplegic CP and how it is affected by task constraints.

COORDINATION OF OBJECT RELEASE
The observed impairments in the coordination of fingertip forces during object replacement and release in children with hemiplegia are in agreement with earlier studies of force coordination during grasping and lifting (Eliasson et al. 1991, 1992, 1995b, 1998; Steenbergen et al. 1998; Forssberg et al. 1999; Gordon and Duff 1999a, b; Gordon et al. 1999; Kuhtz-Buschbeck et al. 2000). Hemiplegic CP is usually the result of middle cerebral artery infarct, hemi-brain atrophy, or posthemorrhagic porencephaly (Uvebrant 1988, Bouza et al. 1994, Okumura et al. 1997). Often the integrity of the motor cortex and corticospinal pathways (see Banker and Larroche 1962, Lademann 1978, Shortland et al. 1988, Uvebrant 1988), which are necessary for precision grip and fine control of the fingers and hand (see Lawrence and Kuypers 1968; Muir and Lemon 1983), are compromised. The resulting damage would impair the ability to finely increase and decrease fingertip forces.

The finding of impaired coordination of object release is also in agreement with our previous studies of children with hemiplegia (Eliasson and Gordon 2000). In both studies, the release phase and the interval between release of each digit from the object were longer in the children with hemiplegia. However, in our earlier study we found that the duration of replacement was actually faster and more abrupt for the child with hemiplegia, whereas in the present study it was slower. This discrepancy is likely to be due to differences in the set-up of the two experiments. In the previous study, children lifted the object for up to 10 seconds, and thus may have become fatigued, allowing the object to passively drop back to the support surface. In the present study, participants held the object for a shorter time, performed fewer trials for each condition, and were given rest as needed. In addition, the object was lifted higher (25.5cm) in the present study compared with the previous one (6cm). Thus unlike the earlier study, muscular effort was required to brake the movement before table contact to avoid damage to the object.

We hypothesized previously that the abrupt replacement of the object could be related to difficulties predicting the distance to the table or a general inability to control motor output (Eliasson and Gordon 2000). The present findings suggest that when required, children with hemiplegic CP may be capable of slowing down the movement and dampening the replacement. This is supported by the tendency of the children with hemiplegia to dampen their velocities just before table contact to a greater extent when accuracy was required, just as the controls did.

Interestingly, the children with hemiplegia decreased their grip force in anticipation of table contact, whereas the children in the control group did not. The pattern seen in the controls is not consistent with previous studies of object release (Gordon 1997, 1998; Eliasson and Gordon 2000), though it should be noted that this task was performed with their nondominant hand which has been shown to influence the coordination of force release (Lewis et al. 2002). The decreased grip force before table contact for the children with hemiplegia could partially compensate for the slower rate of grip force decrease during the subsequent release phase.

THE EFFECT OF VARYING TASK CONSTRAINTS
The children with hemiplegia were able to speed up their movements appropriately when instructed or more carefully replace the object when accuracy was required. Thus they

Figure 7: Mean (±SEM) duration of (a) replacement phase, (b) release phase, and (c) finger difference for non-dominant hand of controls and for non-involved hand of children with hemiplegia for all conditions.
were able to accomplish the task successfully with increased constraints. However, the coordination differences from the age-matched controls were greater when accuracy and/or speed were required (i.e. task performance was affected by these constraints to a greater extent in the children with hemiplegia). It is unclear as to whether the greater effects of task constraints for the children with hemiplegia were directly due to their impaired neural mechanisms or whether they were the result of compensations which allowed successful completion of the task. It is likely that both contributed to the differences, though the issues will require further study.

OBJECT RELEASE WITH NON-INVOLVED HAND
While loss of manual dexterity was not visually discernible in the non-involved hand in any of the children we tested, the present study demonstrated impairments in the temporal coordination of object release in the non-involved hand. This is consistent with our earlier findings of coordination deficits in the non-involved hand during grasping and lifting of objects (Gordon et al. 1999) and with other studies of manual dexterity in children with hemiplegia (Mercuri et al. 1999). The observed impairments are in agreement with the impairments in the non-involved hand function seen in stroke patients with damage to the cortex surrounding the central sulcus or lesions of the internal capsule. For example, left hemispheric lesions have been shown to result in contralateral paresis, as well as more subtle motor impairment of the ipsilateral (left) hand (Kimura 1977, Haaland and Harrington 1989, Marque et al. 1997, Debaere et al. 2001). Both imaging studies (Kawashima et al. 1993, 1994; Kim et al. 1993a, b; Rao et al. 1993; Gordon et al. 1998; Ehrsson et al. 2000; Kuhnt-Buschbeck et al. 2001) and transcranial magnetic stimulation studies (Chen et al. 1997) show ipsilateral motor cortical involvement during unimanual hand tasks. As up to 30% of the fibers in the lateral corticospinal tract remain uncrossed at the motor decussation (Glees and Cole 1952, Nyberg-Hanson and Rinvik 1963, Nathan and Smith 1973), there may be an anatomical substrate for the bilateral impairment in hand function in individuals with hemiplegic CP. The occurrence of bilateral lesions (Wilkund and Uvebrant 1991, Niemann et al. 1994, Okumura et al. 1997, see Mercuri et al. 1999) in some individuals with hemiplegic CP may further impact on fine motor skills in each hand (cf. Bouza et al. 1994).

CLINICAL IMPLICATIONS
The study of object replacement and release from grasp adds to our understanding of impaired hand function in children with hemiplegia. Our results highlight the importance of task and environmental constraints on impairments. As daily activities are likely to involve a variety of environmental constraints, therapists could develop treatment plans that take into account the task constraints which these patients are likely to encounter, particularly high accuracy and speed requirements. Practice with specific task constraints under a variety of conditions may be beneficial. In addition, assistance in developing compensatory strategies to accomplish the tasks successfully under more challenging circumstances may be warranted. Release could be practiced with tasks such as stacking objects varying in fragility and transporting and releasing objects onto stable and unstable surfaces. Performing these tasks at various speeds could further increase the challenge. As the non-involved hand has been found to enhance force coordination in the involved hand (Gordon et al. 1999), practicing release tasks with the non-involved hand first or practicing with bimanual tasks may enhance performance and should be studied.

The finding of impairments in the non-involved hand suggests that clinical attention to the non-involved extremity may also be warranted. As children with hemiplegia use their non-involved extremity for most unimanual tasks (e.g. eating, writing, etc.), evaluating and training the hand to its full capability is particularly important for maximizing the children’s prehensile function.

DOI: 10.1017/S0012162203000471

Accepted for publication 11th December 2002.

Acknowledgments
We wish to extend our gratitude to the parents and children who made this study possible. We thank Maria La Madrid and Amy Shrank for their assistance with participant recruitment. This study was supported by the VIDD foundation.

References


