Journal of Motor Behavior, Vol. 42, No. 3, 2010

RESEARCH ARTICLE

Grip Control in Children before, during, and after Impulsive Loading

Yannick Bleyenheuft, Jean-Louis Thonnard
Physical Medicine and Rehabilitation Unit, School of Medicine, Université catholique de Louvain, Brussels, Belgium.

ABSTRACT. The manipulation of small objects requires continuous contributions from both predictive and reactive mechanisms. The authors aimed to study the development of predictive and reactive mechanisms used by children from 6 to 14 years of age to manage impulsive loading. The load of a handheld object was increased rapidly by the drop of a weight hung on the object. The drop was triggered either by the child (predictive condition) or by the examiner (reactive condition). Regardless of the condition, the control strategy was refined with age. Younger children were unable to adapt their grip force (GF) to the friction of their fingers, whereas the older children provided GF that was well adapted to their variable coefficient of friction, thereby producing a secure grip. This reflected either an inadequate amount of force or an inability to integrate cutaneous information from the fingers in younger children. Additionally, a modulation with age for both predictive and reactive mechanisms was observed. All together, the better predictive abilities and the more secure grip exhibited by older children allow decreased slipping and improved performance in an impulsive loading task.

Keywords: children, children's motor development, precision grip, predictive control, reactive control

The manipulation of objects between the tips of the fingers requires precise coordination between grip force (GF, perpendicular to the grip surfaces) and tangential load force (LF). This coordination is not innate (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991; Forssberg et al., 1992; Forssberg, Eliasson, Kinoshita, Westling, & Johansson, 1995; Gordon, Forssberg, Johansson, Eliasson, & Westling, 1992). In healthy adults the ability to manipulate objects is accomplished by the synchronization of these forces, which are tightly linked to the interaction between predictive control and abundant sensory feedback to ensure reactive control (Witney, Wing, Thonnard, & Smith, 2004). Predictive control allows an individual to anticipate adequate forces to grip the object on the basis of sensorimotor memory (Blakemore, Goodbody, & Wolpert, 1998; Flanagan & Wing, 1997; Witney et al.). In young children, this prehension relies mainly on reactive rather than predictive programming (Forssberg et al., 1991). Additionally, it has been suggested that the use of feedback information is less efficient in younger children (Forssberg et al., 1995). With age, the profile of utilized forces indicates the emergence of a predictive strategy (Forssberg et al., 1991).

Because predictive and reactive controls are less efficient in children, studying the development of each requires tasks that can dissociate the two types of control. Rapid changes in force applied to a handheld object (impulsive loading) provide a good paradigm to investigate both controls because the same event can arise in expected and unexpected conditions.

In the present investigation, an impulsive loading task was generated by dropping a mass attached to a handheld object. Because no visual cues were available, the task could be randomly induced by the child (predictive condition) or the examiner (reactive condition). Children's ability to adapt to sudden changes in forces has been previously studied in both unloading (Schmitz & Assaiante, 2002; Schmitz, Martin, & Assaiante, 1999, 2002) and increases of LF (Eliasson et al., 1995). In this last experiment, the ability to anticipate and react to a sudden load increase has been studied in a task during which the load of a handheld object was increased rapidly by the drop of a ball onto a test object. The drop was carried out either by the participant or unexpectedly by the examiner. The younger children showed, on average, lower values for the anticipatory grip force (GF at impact) and the delay of the anticipatory adjustments decreased with age (Eliasson et al). Eliasson et al. described the ability to anticipate the rapid increase of a handheld object regarding the aptitude to increase GF prior to the impact. However, in a recent study we showed with adult participants that prediction of the movement continues after a self-triggered impact, regulating the maximum of GF that arises after the impact (Bleyenheuft, Lefèvre, & Thonnard, 2009). It has never been studied through childhood. Moreover, in Eliasson et al.'s study, children had, in predictive conditions, visual and prorioceptive information. As it has been evidenced that children older than 3 years of age presented greater visual influences on motor programming than adults (Gordon et al., 1991), the absence of visual information in our a protocol may lead to different results.

We investigated the events before, during, and after impulsive loading in both conditions. Through this broad analysis, we aimed to study the control strategy used by children to perform an impulsive loading task in its entirety and the developmental changes in this strategy that occur with age. Refinement of the grip control strategy with age could explain the awkwardness of young children in impulsive loading tasks.

We hypothesized that our results would be, at least partly, related to those of Eliasson et al. (1995), showing variation in anticipation profile for timing and magnitude of forces. We also expected to find some variation in the ability to control the last part of the anticipation in predictive conditions.

Correspondence address: Jean-Louis Thonnard, Université catholique de Louvain, Unité de réadaptation et de médecine physique, Avenue Mounier 53, 1200, Bruxelles, Belgium. e-mail: jean-louis.thonnard@uclouvain.be

Method

The present study was authorized by the Ethical Committee of the Université catholique de Louvain, Faculty of Medicine in Brussels, Belgium. Participants and parents gave their written informed consent.

Seventy-five healthy Belgian boys homogeneously distributed between 6 and 15 years of age (*M* age = 10.6 years *SD* = 2.48) were assessed. They were all recruited from schools in the city of Brussels. Absence of a cognitive deficit, as attested by a normal school level and parents' notification, was a selection criterion to be included in this study.

Apparatus

The apparatus used to measure fingertip forces (Figure 1) was a cylindrical object (80 mm diameter, 30 mm width, 220 g mass) equipped with two brass circular grip surfaces (40 mm diameter) placed on two parallel lightweight force-torque sensors (Mini40 F/T transducer; ATI Industrial Automation, Apex, NC, USA). GF and tangential forces (TF) were calculated on the basis of the three forces (Fx, Fy, Fz) components measured by each sensor. Fx, Fy, and Fz sensing ranges were ± 40, ± 40, and ± 120 N, with 0.002, 0.002, and 0.006 N resolution, respectively. LF, tangential to the grip surface, was the result of the vectorial sum of Fx and Fy, and the force normal to the GF was given by Fz.

The horizontal and vertical centers of pressure were also measured. An open table was used as a support for the object. A steel mass (100 g) was attached to the object via a Kevlar string. An electromagnet allowed an individual to place the steel mass a few centimeters above its lowest position and freely lift the object.

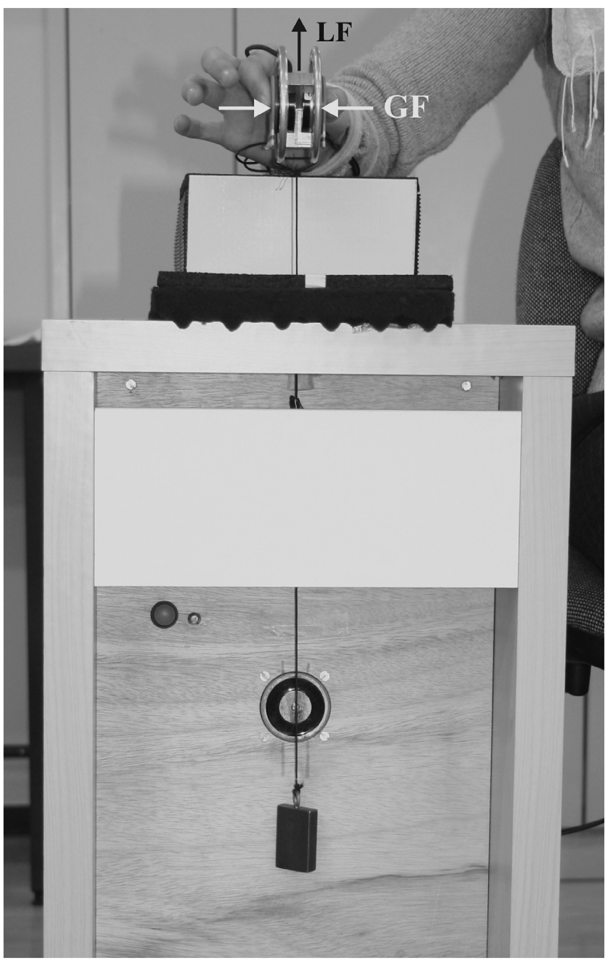

FIGURE 1. The setup used to perform the task. The forces applied on the object during the task are illustrated by white and black arrows that refer to grip force (GF) and load force (LF), respectively.

Procedure and Experimental Protocol

First, children were asked to wash and dry their hands. The task was then clearly explained to each child. Children sat next to the table, which provided support to the forearm (Figure 1), and were asked to grip the object with a spontaneous precision grip and to maintain it at a given position. They held a push-button switch in their nondominant hand.

In predictive conditions, the children pressed the switch in response to an auditory signal. The switch instantaneously turned off the magnetic field and led to a 4-cm drop of the mass and a consequent sudden LF increase (impact). Importantly, no noise was associated with the steel mass leaving the electromagnet. In reactive conditions, children were confronted with an unpredictable impact, as the drop was triggered by the examiner (no auditory cue). Because in predictive condition the auditory cue appeared unevenly in the 30 s duration of each trial, the children were unable to guess whether there would be a cue or not, and when it would appear. In both conditions, after the drop of the additional mass, the total mass of the handheld object was of 320 g.

The task was carried out with the dominant hand: 20 trials in the predictive and 10 in the reactive conditions were intermingled following a random sequence. The trials as a whole were directly preceded as well as followed by four lift-and-drop maneuvers to measure the coefficient of friction (CF). Each participant had to grip the stationary object and then relax the GF until it slipped. The CF was calculated as 0.5 LF/GF at the onset of the slip, which was detected on the left and right centers of pressure (vertical axis). Because no significant difference appeared between the index and thumb values (Friedman analysis, $p = .128$), the mean value between both measures was computed. For each participant, the four measures of friction taken before the task were averaged with the four measures of friction performed afterwards to provide a single reliable CF measure. Before starting the test, three measures of the maximal voluntary contraction (MVC) between the thumb and index finger were registered directly on the test object. The MVC was measured on half of the participants.

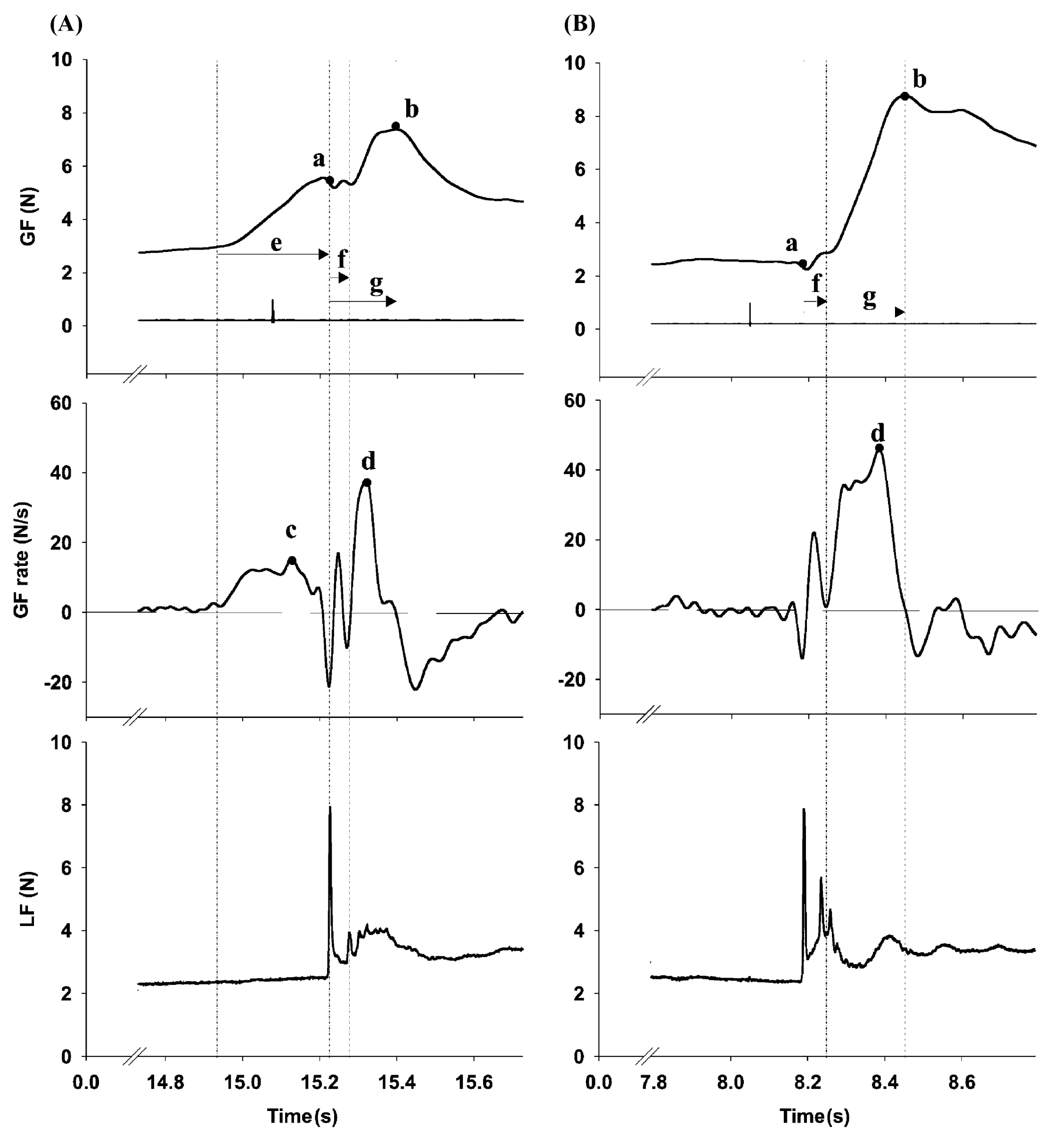

FIGURE 2. Typical recording of grip force (GF), GF rate, and load force (LF) traces during the impact phase of an 11-year-old child during (**A**) the sixth predictive trial and (**B**) the sixth reactive trial. In (**A**), the four vertical dotted lines represent, from left to right, the onset of GF increase before impact, the impact time, the onset of GF increase after impact, and GF max time. In (**B**), the three vertical dotted lines represent the impact time, the onset of GF increase after impact, and GF max. a = GF at impact; b = GF max; c = GF max rate before impact; d = GF max rate after impact; e = anticipatory delay; f = delay between impact and GF increase after impact; g = delay between impact and GF max.

Data Acquisition and Analysis

The signals from the force sensors were digitized online at 1000 Hz with a 12-bit 6071E analog-to-digital converter in a PXI chassis (National Instruments, Austin, TX, USA). After analog-to-digital conversion, the GF and GF rate signals were further low-pass filtered with a fourth-order, zero phase-lag Butterworth filter having a cut-off frequency of 15 Hz.

Force and time events were measured on each trace. A stable phase, which was visually determined thanks to the stability in the LF trace, provided reference values during the waiting period that preceded the impact phase. During this stable phase, a mean GF and a mean safety margin (SM) were calculated (SM = GF—GF at slip where GF at slip = 0.5 LF / CF).

During the impact phase, dynamic and temporal variables were measured (Figure 2). The dynamic variables included the GF at impact (Figure 2, a), the maximum GF (GF max; Figure 2, b), the maximum GF rate before impact (Figure 2, c), the maximum GF rate after impact (Figure 2, d), and the safety margin at impact. The temporal parameters included the anticipatory delay (Figure 2, e), the delay between impact and the GF increase after impact (postimpact delay; Figure 2, f), and the delay between impact and GF max (delay to GF max; Figure 2, g).

In the reactive condition, the same variables were investigated with the exception of anticipatory delay and GF rate max before impact. The three delays described here above could be identified in all trials. In case of slip and fall of the object after impact, the data were loss for the postimpact events and were considered as missing value.

In both conditions, the numbers of slips were counted. A slipping event during a trial occurred when the fingers of the subject left the contact surfaces, thereby leading to the fall of the object. GF rate max, GF max, and the impact (LF max) were designated on each trial by the absolute maxima in the impact phase.

Statistics

The potential effects of training were studied using a repeated measures analysis of variance ($ANOVA_{RM}$) or a Friedman analysis when normality failed on each variable studied separately in predictive and reactive condition. This analysis showed that the only trial that differed from the others was the first one. Consequently, mean values used for the subsequent analysis were calculated from the second trial for each participant, in both the predictive and reactive modes.

$ANOVA_{RM}$ or a Friedman analysis when normality failed was used to compare the mean values of each child in predictive and reactive conditions. The age effect was tested with the Pearson or Spearman correlation between the mean value of the variables and the age of the children on the date of the test for the predictive condition. A similar analysis was conducted for the reactive conditions. To further investigate the gradual refinement of precision grip with age, children were classified in four age groups (6–7, 8–9, 10–11, and 12 years or older) that were compared using an ANOVA or an ANOVA on ranks (Kruskall–Wallis test) when normality failed. A Tukey post hoc test was used to determine which groups were significantly different.

Results

Figure 2 illustrates the typical GF, GF rate, and LF traces in predictive and reactive modes. In predictive conditions, the child increased the GF before the impact. The impact was detected as a sharp increase in LF. Subsequently, a second increase in GF was obvious after the impact, leading to the GF max. In reactive conditions, the GF began to increase to its maximum after the impact.

The means and standard deviations of the variables are displayed in Table 1 for the predictive and reactive conditions. The comparison between the two conditions showed that, in the reactive mode, the GF at impact (Friedman analysis), χ^2 $(df = 1; n = 75) = 49.630$, $p < .001$, and SM at impact

TABLE 1. Mean Values of Variables and Age Effects

	Values		Correlation with age	
Variables	Mean	±SD	r	P value
Predictive conditions				
GF stable phase (N)	3.2	1.28	0.35	0.003*
GF at impact (N)	5.1	2.32	0.32	0.006*
GF max (N)	7.7	3.36	0.24	0.046*
SM stable phase (%)	55	16.4	0.57	<0.001*
SM at impact (%)	68	14.9	0.57	<0.001*
GF rate max before I (N/s)	18	13.4	0.112	0.345
GF rate max after I (N/s)	42	17.1	0.2	0.092
D anticipation (ms)	−327	90	0.15	0.217
D post-impact (ms)	51	7	−0.41	<0.001*
D to GFmax (ms)	167	42	−0.42	<0.001*
Reactive conditions				
GF stable phase (N)	3.2	1.28	0.38	<0.001*
GF at impact (N)	3.4	1.52	0.31	0.008*
GF max (N)	7.5	3.72	0.31	0.008*
SM stable phase (%)	60	16.9	0.5	<0.001*
SM at impact (%)	57	21	0.56	<0.001*
GF rate max after I (N/s)	55	34.5	0.38	<0.001*
D post-impact (ms)	61	7	−0.15	0.196
D to GFmax (ms)	225	5	−0.35	<0.001*
MVC (N)	25.1	10.68	0.77	<0.001*

GF = grip force; D = delay; MVC = maximal voluntary contraction; I = impact.

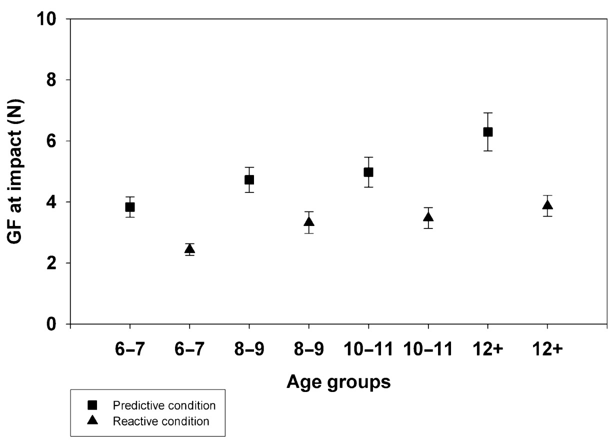

FIGURE 3. Plots showing the mean values and standard error of grip force (GF) at impact in the four age groups in predictive (square plot) and reactive (triangle) conditions.

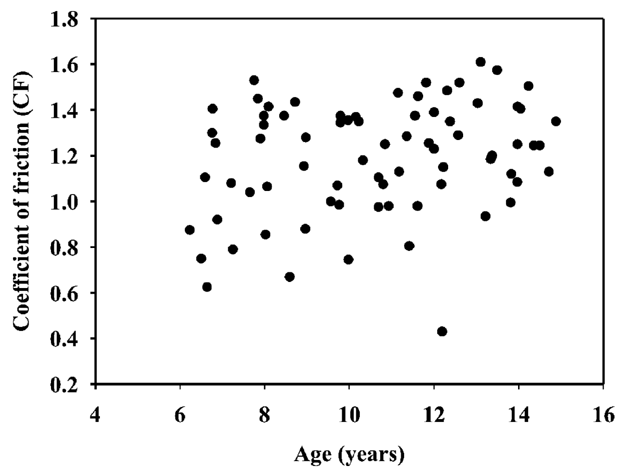

FIGURE 4. Wide distribution of the coefficient of friction through childhood.

(Friedman analysis), $\chi^2(df = 1; n = 75) = 59.830, p < .001$, were lower (Figure 3). The same pattern was observed for the GF max (Friedman analysis), $\chi^2(df = 1; n = 75) = 4.813, p = .028$, but the GF max rate after impact was higher in the reactive mode (Friedman analysis), $\chi^2(df = 1; n = 75) = 7.083, p = .008$. The temporal variables, including the postimpact delay ($ANOVA_{RM}$), $F(dfs = 74;1) = 165.08, p < .001$, as well as the delay to GF max ($ANOVA_{RM}$), $F(dfs = 74;1) = 123.46$, $p < .001$, were significantly longer in the reactive condition.

Table 1 shows the mean value of the variables and the correlations between these variables and age for each condition. The *p* values in Table 1 refer to the correlations only. The *p* values associated with the comparisons by condition for each variable are listed in the preceding paragraph.

In the predictive condition, the postimpact delay decreased significantly with age (Figure 2, f) and delay to GF max also decreased with age (Figure 2, g). In the reactive condition, the delay to GF max also decreased with age. Furthermore, the GF max rate after impact increased with age in reactive conditions.

Grip Control Strategy

Table 1 shows age-dependent effects on GF max, GF, and SM during the stable phase and at impact time for both conditions. Interestingly, Figure 4 shows that the coefficient of friction was widely distributed between 0.4 and 1.5 among our sample of children.

Figure 5 displays the relationship among age, GF, and SM during the stable phase in the predictive and reactive conditions. In both conditions, the range of GF increased significantly with age (Figure 5A and B, Table 1) and the degree of adaptation to the wide range of CF was improved. As a consequence, the SM during the stable phase was more consistent with age. The SM during the stable phase was concentrated between 60% and 80% for all participants aged around 14 years (Figure 5C and D). Similar effects were also seen for GF measurements (at impact and GF max) and SM at impact (Table 1).

These effects on GF and SM were confirmed by conducting a comparison between four age groups (6–7, 8–9, 10–11, and 12 years or older) with an ANOVA (or a Kruskall-Wallis test). Significant differences between groups were shown for GF during stable phase and at impact in both conditions (all *p*s $< .025$), for GF max in the reactive condition ($p = 0.038$), for SM in stable phase and at impact in both conditions (all *p*s $< .001$). The Tukey post hoc tests showed systematically differences between the 6–7 years and 12 years or older groups. Differences were also observed between the 6–7 years and 10–11 years groups and between the 8–9 years and 12 years or older groups. Therefore, we suggest that the refinement of the GF adjustments for such a task pursues until 10 years of age.

This is confirmed by the improvement of adaptation to the wide range of CF with age that can be better shown when considering the correlation among GF and CF in three age groups: the children aged 6–9 years, 10–11 years, and 12 years or older. As illustrated in Figure 6A, for children younger than 9 years of age, no correlation was noticed between GF and CF. This was true for all GF measurments (during stable phase, at impact, GF max) in the predictive and reactive conditions (Spearman correlation; all *p*s $> .590$). For children older than 10 years of age, correlations were observed between GF and CF during stable phase in the predictive and reactive conditions ($r = -.408$, $p = .007$; $r = -.396$, $p = .008$, respectively; Figure 6B).

These results were strengthened by a significant decrease with age in the percentage of slips observed during the task in predictive and reactive conditions ($r = -.833$ and $r = -.810$, respectively; all *p*s $< .004$). Indeed, the percentage of slips in predictive conditions decreased from 10% at 6 years of age to 0% at 14 years of age; in reactive conditions it

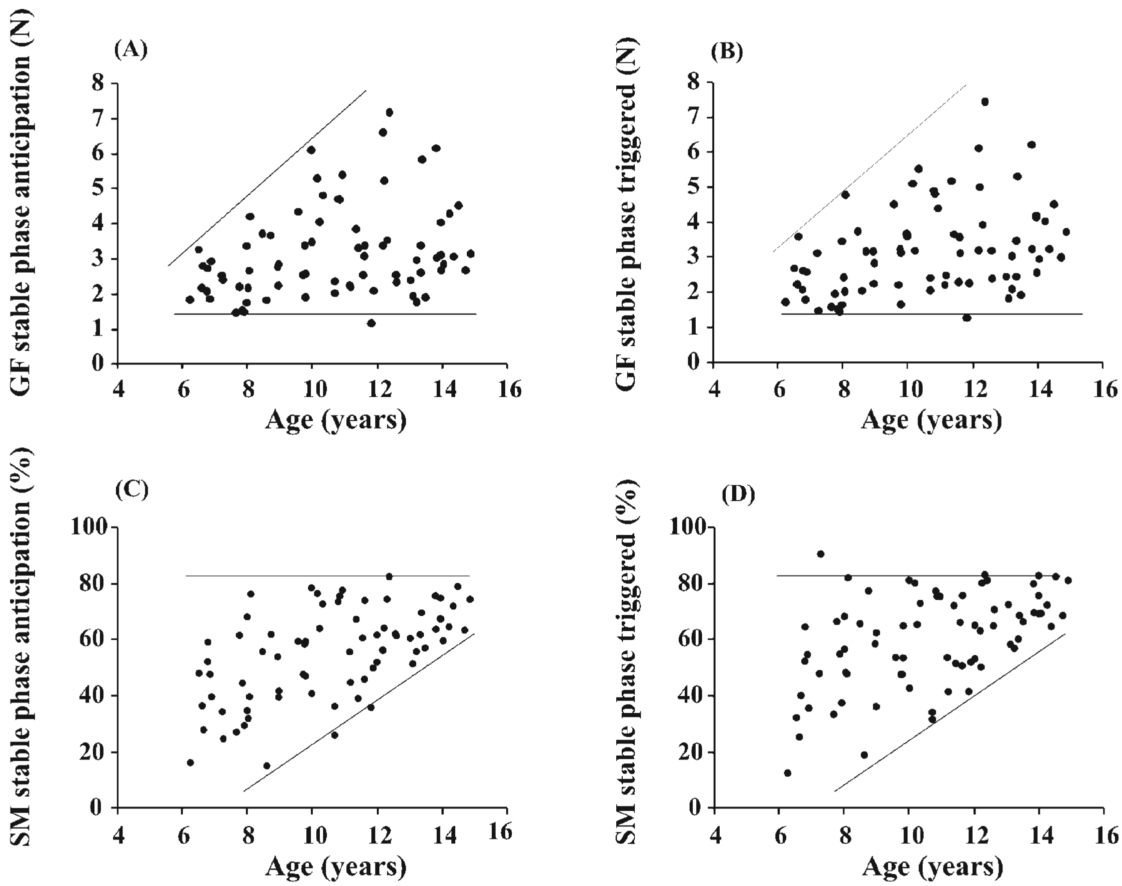

FIGURE 5. Plots showing the relationship between age and grip force (GF) during the stable phase for all children in the (**A**) predictive and (**B**) reactive modes. Black lines underlie the more diversified GF level used by older children. Illustration of the correlation between age and safety margin (SM) during the stable phase for all children in the (**C**) predictive and (**D**) reactive modes. Black lines underlie the more consistent GF level used by older children.

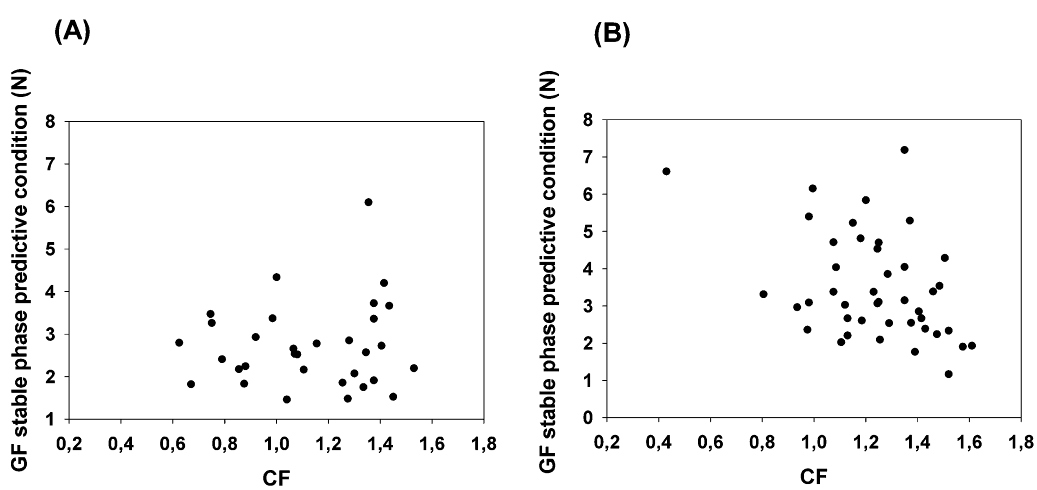

FIGURE 6. Plots showing the relationship between grip force (GF) in stable phase in predictive condition and the coefficient of friction (CF) for children (**A**) between 6 and 9 years old and (**B**) children aged 10 years or older.

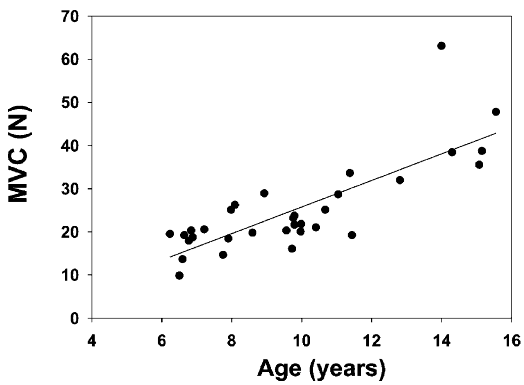

FIGURE 7. Illustration of the evolution of the maximal bidigital force (MVC) with age.

reached 18% in 6-year-old children and decreased until 14 years of age in which no slips were observed. The bidigital MVC increased significantly with age (Figure 7, Table 1). As a consequence, the percentage of MVC used by the children to perform the task during the stable phase decreased from 30% for the youngest to 5% for the older children. For GF max, the variation ranged from 60% to 15%.

Discussion

In the present experiment, we aimed to study the control strategy used by children before, during, and after an impulsive loading task and the developmental changes encountered in this strategy.

Previous studies have investigated the ability of children to adapt to sudden changes in forces in both unloading (Schmitz & Assaiante, 2002; Schmitz et al., 1999, 2002) and loading conditions (Eliasson et al., 1995). In the loading experiment, young children were confronted with an impact that was triggered either by the child (predictive condition) or the examiner (reactive condition). We analyzed events prior to impact in predictive conditions and after the impact in reactive conditions. In contrast, we investigated whether the performance of the task was influenced by the grip strategy before, during, and after the impulsive loading (Cole & Rotella, 2001). Some age-related effects on grip control strategy were observed, especially an inability of the youngest children to adapt their grip forces to different CF levels. Notable differences between pure reactive and predictive conditions were observed in the GF rate after impact and in the delay postimpact. The data showed an age-dependent modulation in task achievement because the delays in increasing GF after impact in the predictive condition and in reaching GF max were reduced with age.

Grip Control Strategy

Age effects were evident in GF and SM in the predictive and reactive conditions during the entire task. The GF levels of older children were more diversified, whereas the GF levels of younger children were concentrated around 2 or 3 N during the stable phase. Because the CF was highly variable among children of all ages, the variation in force levels in the older children was in fact a good adaptation to the different CF values. This hypothesis was supported by the consistency of the safety margins (all around 60–80% during the stable phase). Conversely, the younger children presented large variations in their safety margins as they always exerted GF in the same range while their CF was variable. This age-dependent adaptation of the grip level to CF further showed the inability of younger children to adequately adapt their force to friction in the case of an impulsive loading.

One explanation to account for the decreased adaptation of GF in younger children is their lack of force. Muscle strength develops during growth (Beenakker et al., 2001) as the development of muscle force increases during childhood and stabilizes at around 14 years of age. This is consistent with findings of a strong correlation between age and the MVC in our study. Furthermore, the percentage of MVC used to perform the task decreased with age. In normal adult participants, a percentage of MVC up to 20% is considered to be a low-intensity contraction for the first dorsal interosseus (Maluf, Shinohara, Stephenson, & Enoka, 2005). In position tasks involving repetitive conditions of higher intensities, the participants could not sustain contractions for durations longer than 40 s (Maluf et al.). In the present study, for some of the younger children, the percentages of MVC were higher than 20%. Consequently, we believe that the younger children did not use higher GF because it could have led to an early failure and thus an inability to perform the task. Additionally, the SM became more consistent in our study once children reached around 13–14 years of age. This age closely matches the age at which the development of force reaches adult values (Beenakker, van der Hoeven, Fock, & Maurits, 2001). A complementary explanation for this lower adaptation of GF to friction could be an immature integration of information from the cutaneous afferents. The GF/LF ratio was indeed adapted as a function of the CF (Cadoret & Smith, 1996).

In a classical load-lifting task, Forssberg et al. (1995) showed that children started to adapt their GF to different contact surfaces from the second year. At this age, they needed repetitive presentation of the surface, which suggested either an inability to form a sensorimotor memory or an inability to use this representation to define the required force ratio. The adaptation to different surfaces was refined afterwards, but was still not similar to that of adults at 13 years of age (Forssberg et al.). This was consistent with the idea that mental representation varies with age and is dependent on experience (Paré & Dugas, 1999). With age, children could thus build a directory of sensorimotor experience, thereby allowing for better adaptation to different grip conditions. Whatever the underlying mechanism, this different strategy used by the youngest children could be responsible, at least partly, for their more frequent instances of slips.

Comparison of Predictive and Reactive Conditions

The GFmax rate after impact was significantly lower in the predictive condition than in the reactive condition. This was consistent with the adult data in which the amplitude of GF rate after impact was higher in the reactive condition than in the predicted condition (Johansson & Westling, 1988). This could be due to the fact that, in predictive conditions, the motor program that controls preliminary actions significantly reduced the motoneuronal activity in the triggered component after an impact. In a previous study, Asai and Aoki (1996) showed that the maximal rate of force development decreased linearly while the pre-tension increased. They showed that during pre-tension, small motor units corresponding to slow fibers are recruited to maintain the pre-tension level. Gradually, as pre-tension increases, motor units from rapid fibers are recruited as well. Therefore, the subsequent isometric contraction started earlier, but with a lower velocity because some rapid fibers had already been recruited.

In the present study, the increase in GF after impact appeared earlier in predictive than in reactive conditions. This could be due to a larger pre-tension of the fibers as discussed previously or the fact that in the predictive conditions this increase is due to a predictive mechanism. Indeed, evidence from deafferented patients and from normal adults allows researchers to question the pure reactive aspect of this increase in GF after impact. First, in predictive conditions, this increment after impact has been observed in deafferented patients, whereas no reaction was obtained in reactive conditions (Nowak & Hermsdorfer, 2006). Second, while performing unexpected trials without impact in predictive conditions, an increase in GF could still be observed after the impact (Johansson & Westling, 1988). We recently evidenced that this increase in GF after a self-triggered impact is of a predictive nature (Bleyenheuft et al., in press). This could therefore start the GF increase after impact earlier than a reflex mechanism in pure reactive situations.

Age Effects During the Impact Phase

Age effects were demonstrated in the delay to GF max in reactive and predictive conditions, as the delays were shorter for older children. In reactive conditions, the shortening of this delay could be explained by an increase of GF rate max after impact due to muscular modifications. The increase in GF rate max with age was consistent with the results from Eliasson et al. (1995), which showed an increase of GF rate with age (although it did not reach adult values even in 9–10-year-olds). The maximum rate of force development was tightly linked to the speed of muscle contraction, and this was dependent on the recruitment of a different motor unit (MU). Normal adult subjects presented a higher recruitment of large MUs (corresponding to rapid fibers) than did children (Halin, Germain, Bercier, Kapitaniak, & Buttelli, 2003), and this larger MU recruitment allowed for a higher rate of muscle contraction.

In predictive conditions, no modification of GF rate was observed to explain the reduction of the delay to GF max with age. Because both predictive and reactive components were probably included in this GF increase in predictive conditions, we suggested that, as for the postimpact delay, the decrease with age indicated maturational processes in the ability to program a self-triggered perturbation. It has been suggested that this GF increment arose after impact in order to maximize the damping at the moment of the collision (Delevoye-Turrell, Li, & Wing, 2003) and to stabilize hand posture afterwards. We suggest that this ability is refined with age. This may be consistent with other refinements in precision grip, such as the adaptation to contact surfaces or different weights with age (Forssberg et al., 1992; Forssberg et al., 1995).

Interestingly, the postimpact delay decreased with age in predictive but not in reactive conditions. This was consistent with previous results that showed that in reactive conditions stable values were obtained for this postimpact delay beginning when children reached 5 years of age (Eliasson et al., 1995). In contrast, the postimpact delay clearly evolved with age in predictive conditions, reinforcing the hypothesis that a different method of processing is used to increase GF after impact in predictive and reactive conditions. In fact, this observation further supports the idea that, in predictive conditions, the handling of perturbations and the subsequent increase in GF were planned as a feedforward action. This greater adjustment of the delays with age was consistent with results from previous studies of children performing unloading tasks (Schmitz et al., 2002). In sequences where the children anticipated a voluntary unloading, the precise mastering of the timing parameters was a factor that matured later in childhood (Schmitz et al.). In the context of impulsive loading, the refinement of delays with age seemed to evolve into more efficient movement evidenced by a reduction in the number of slips.

Conclusion and Perspectives

In conclusion, we have shown that the efficiency of GF strategy matured with age in an impulsive loading task as the safety margin reached identical—and comfortable—values only when the children reached 13–14 years of age. These observations emphasize the inability of young children to adequately adapt their force to the friction between the object and their fingers to manage an impulsive loading task. Additionally, this study highlights the evolution of predictive and reactive mechanisms with age in a perturbation task. We suggest that, in predictive conditions, the maturation of central processes has a major influence on the ability to program a movement until the GF max level after impact. Conversely, when a perturbation was unpredictably triggered, peripheral muscular properties were clearly involved in the development of reactive mechanisms. All together, the shortening of delays and the larger SM in the older children resulted in a decreased number of slips and thus a better performance of impulsive loading tasks relative to younger children.

Future researchers should investigate control strategies as well as predictive and reactive mechanisms in pathological cases to identify the origin of prehension deficits. These research questions may be particularly interesting in children with cerebral palsy whose prehension impairments are sometimes attributed to deficits in predictive abilities and perturbed feedback. Further investigation into impulsive loading may allow for a better understanding of impaired control mechanisms and thus permit the design of more adequate rehabilitation programs.

REFERENCES

Asai, H., & Aoki J. (1996). Force development of dynamic and static contractions in children and adults. *International Journal of Sports Medicine*, *17*, 170–174.

Beenakker, E. A., Van Der Hoeven, J. H., Fock, J. M., & Maurits, N. M. (2001). Reference values of maximum isometric muscle force obtained in 270 children aged 4–16 years by handheld dynamometry. *Neuromuscular Disorders*, *11*, 441–446.

Blakemore, S. J., Goodbody, S. J., & Wolpert, D. M. (1998). Predicting the consequences of our own actions: The role of sensorimotor context estimation. *Journal of Neuroscience*, *18*, 7511–7518.

Bleyenheuft, Y., Lefèvre, P., & Thonnard, J. L. (2009). Predictive mechanisms control grip force after impact in self-triggered perturbations. *Journal of Motor Behavior*, *41*, 411–417.

Cadoret, G., & Smith, A. M. (1996). Friction, not texture, dictates grip forces used during object manipulation. *Journal of Neurophysiology*, *75*, 1963–1969.

Cole, K., & Rotella, D. (2001). Old age affects fingertip forces when restraining an unpredictably loaded object. *Experimental Brain Research*, *136*, 535–542.

Delevoye-Turrell, Y. N., Li, F. X., & Wing, A. M. (2003). Efficiency of grip force adjustments for impulsive loading during imposed and actively produced collisions. *Quaterly Journal of Experimental Psychology*, *56*, 1113–1128.

Eliasson, A., Forssberg, H., Ikuta, K., Apel, L., Westling, G., & Johansson, R. (1995). Development of human precision grip. V. Anticipatory and triggered grip actions during sudden loading. *Experimental Brain Research*, *106*, 425–433.

Flanagan, J. R., & Wing, A. M. (1997). The role of internal models in motion planning and control: Evidence from grip force adjustments during movements of handheld loads. *Journal of Neuroscience*, *17*, 1519–1528.

Forssberg, H., Eliasson, A. C., Kinoshita, H., Johansson, R. S., & Westling, G. (1991). Development of human precision grip. I. Basic coordination of force. *Experimental Brain Research*, *85*, 451–457.

Forssberg, H., Eliasson, A. C., Kinoshita, H., Johansson, R. S., Westling, G., & Gordon, A. M. (1992). Development of human precision grip. II. Anticipatory control of isometric forces targeted for object's weight. *Experimental Brain Research*, *90*, 393–398.

Forssberg, H., Eliasson, A. C., Kinoshita, H., Westling, G., & Johansson, R. S. (1995). Development of human precision grip. IV. Tactile adaptation of isometric finger forces to the frictional condition. *Experimental Brain Research*, *104*, 323–330.

Gordon, A. M., Forssberg, H., Johansson, R. S., Eliasson, A. C., & Westling, G. (1992). Development of human precision grip. III. Integration of visual size cues during the programming of isometric forces. *Experimental Brain Research*, *90*, 399–403.

Halin, R., Germain, P., Bercier, S., Kapitaniak, B., & Buttelli, O. (2003). Neuromuscular response of young boys versus men during sustained maximal contraction. *Medicine and Science in Sports and Exercise*, *35*, 1042–1048.

Johansson, R. S., & Westling, G. (1988). Programmed and triggered actions to rapid load changes during precision grip. *Experimental Brain Research*, *71*, 72–86.

Maluf, K. S., Shinohara, M., Stephenson, J. L., & Enoka, R. M. (2005). Muscle activation and time to task failure differ with load type and contraction intensity for a human hand muscle. *Experimental Brain Research*, *167*, 165–177.

Nowak, D. A., & Hermsdorfer, J. (2006). Predictive and reactive control of grasping forces: On the role of the basal ganglia and sensory feedback. *Experimental Brain Research*, *173*, 650–660.

Paré, M., & Dugas, C. (1999). Developmental changes in prehension during childhood. *Experimental Brain Research*, *125*, 239–234.

Schmitz, C., & Assaiante, C. (2002). Developmental sequence in the acquisition of anticipation during a new co-ordination in a bimanual load-lifting task in children. *Neuroscience Letters*, *330*, 215–218.

Schmitz, C., Martin, N., & Assaiante, C. (1999). Development of anticipatory postural adjustments in a bimanual load-lifting task in children. *Experimental Brain Research*, *126*, 200–204.

Schmitz, C., Martin, N., & Assaiante, C. (2002). Building anticipatory postural adjustment during childhood: A kinematic and electromyographic analysis of unloading in children from 4 to 8 years of age. *Experimental Brain Research*, *142*, 354–364.

Witney, A. G., Wing, A., Thonnard, J. L., & Smith, A.M. (2004). The cutaneous contribution to adaptive precision grip. *Trends in Neurosciences*, *27*, 637–643.

Submitted May 17, 2009
Revised October 2, 2009
Accepted November 9, 2009