



Review article

Precision grip control, sensory impairments and their interactions in children with hemiplegic cerebral palsy: A systematic review[☆]

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ABSTRACT

Children with hemiplegic cerebral palsy (HCP) exhibit long-term functional deficits. One of the most debilitating is the loss of prehension since this may impair functional independence. This loss of prehension could be partly due to sensory deficits. Identifying the underlying causes of prehension deficits and their potential link with sensory disorders is important to better adapt neurorehabilitation.

Here we provide an overview of precision grip and sensory impairments in individuals with HCP, and the relation between them, in order to determine whether the sensory impairments influence the type and magnitude of deficits as measured by studies of prehensile force control.

Pubmed and Scopus databases were used to search studies from 1990 to 2012, using combinations of the following keywords: fingertip force; grip force; precision grip; sensory deficit; sensory impairment; tactile discrimination; with cerebral palsy. Of the 190 studies detected through the systematic search; 38 were finally included in the systematic part of this review.

This review shows that sensory deficits are common and are likely underestimated using standard clinical assessments in HCP. Some studies suggest these deficits are the basis of predictive motor control impairments in these individuals. However, children with HCP retain some ability to use predictive control, even if it is impaired in the more affected hand. Intensive practice and initial use of the less affected hand, which has only subtle sensory deficits, has been shown to remediate impairments in anticipatory motor control during subsequent use of the more affected hand. Implications for motor and sensory rehabilitation of individuals with HCP are discussed.

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1. Introduction – background

Cerebral palsy occurs in 2–3.6 out of 1000 children (Murphy, Yeargin-Allsopp, Decouflé, & Drews, 1993; Stanley, Blair, & Alberman, 2000; [cdc.gov](http://www.cdc.gov): <http://www.cdc.gov>). Among the different clinical forms of cerebral palsy, hemiplegic cerebral palsy (HCP) is one of the most common, affecting ~30% of the children with CP (Stanley et al., 2000). One of their most debilitating long-term functional deficits is impaired manual dexterity (Uvebrant, 1988). In pediatric HCP, skilled hand movements are typically impaired and there are sensory impairments as well. One approach used to quantify these impairments is the study of the coordination of fingertip forces during object manipulation using the precision grip (Eliasson, Gordon, & Forssberg, 1991, 1992, 1995a; Forssberg, Eliasson, Redon-Zouitenn, Mercuri, & Dubowitz, 1999; Gordon & Duff, 1999a, 1999b; Gordon, Charles, & Duff, 1999; Mackenzie, Getchell, Modlesky, Miller, & Jaric, 2009). This task is ideal as it has been shown through digital nerve block (Augurelle, Smith, Lejeune, & Thonnard, 2003; Johansson, Hger, & Bäckström, 1992; Monzée, Lamarre, & Smith, 2003), and force adaptation to texture (Johansson & Westling, 1988) in healthy subjects that the integrity of sensory information is necessary for precision grip tasks. Thus systematically describing precision grip and sensory impairments in children and adolescents with HCP and the relationship between both could help understanding whether the sensory impairments influence the type and magnitude of deficits observed in precision grip for these children. We also discuss how the specific impairments documented have influenced the neurorehabilitation practice to develop new interventions, notably unimanual intensive practice adapted to children with HCP and bimanual interventions, and how this knowledge may continue to help us to more precisely focus neurorehabilitation interventions in the future.

1.1. Precision grip

Precision grip, even in simple tasks such as a grip-lift movement, requires a subtle coordination between the grip force (GF, perpendicular to contact surfaces) and tangential load forces (LF) opposing gravity (Johansson & Westling, 1984, 1988). Both tactile information (signaled by slow and fast adapting afferents, Westling & Johansson, 1987) and weight-related information (signaled by muscle spindles and tactile afferents) are used during grasping and object manipulation to adapt the fingertip forces to the object's physical properties (Johansson, 1996). However, due to delays in the transmission of sensory information, such information signaling the object's physical characteristics is not immediately available. To avoid dropping or crushing objects, the fingertip forces must be scaled (planned) before the initiation of the movement to match the object's expected properties based on internal representations of the object gained during prior manipulatory experience (Johansson & Westling, 1987, 1988; Gordon, Westling, Cole, & Johansson, 1993). Such 'anticipatory control' of the force output is characterized by continuous grip and load force increase in parallel (force coupling), with the rate of force increase scaled from the onset toward the target load force (i.e. faster rates for heavier or more slippery objects). Fig. 1 (left panel) shows the normal force application during a prehension (grip/lift) task in healthy adults. During the preload phase (a), GF increases prior to LF onset. Afterwards, both GF and LF increase in parallel during the loading phase (b). The rate of the forces during this forces increase is characterized by single peaks that are well-timed. After a static phase, the release of the object (see right panel of Fig. 1) is characterized by a replacement phase (T0–T1) where the object is repositioned on the table, followed, after the contact with the table, by a rapid decrease in the grip and load forces (T1–T2) until the digits are removed from the object in quick succession (T2–T3).

The grip and lift parts of object manipulation have been largely studied. The parallel development of grip force (GF) and load force (LF) is also particularly well highlighted when the GF is plotted relative to LF (see right lower panel, Fig. 2). Adaptation to different friction and load conditions during the grip and lift phases has been well demonstrated (Fig. 2A and B). In typically developing children, this coordination between GF and LF approximates that of adults around 8–10 years of age (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991). Before this age, as showed by Forssberg and colleagues (Fig. 3) children showed a reversed coordination whereby the object is pressed downward against the table inducing a large GF and a negative LF. During the loading phase, the GF and the LF are not generated in parallel but sequentially. Indeed, the greatest part of the total GF is generated during the preload phase before the load forces are initiated.

Bimanual precision grip tasks have been investigated recently in order to examine fingertip forces coordination in the two hands when opposite or concomitant patterns of force are required in the hands (Islam, Gordon, Sköld, Forssberg, & Eliasson, 2011; Smits-Engelsman, Klingels, & Feys, 2011). For instance placing a handheld object on the top of another object statically

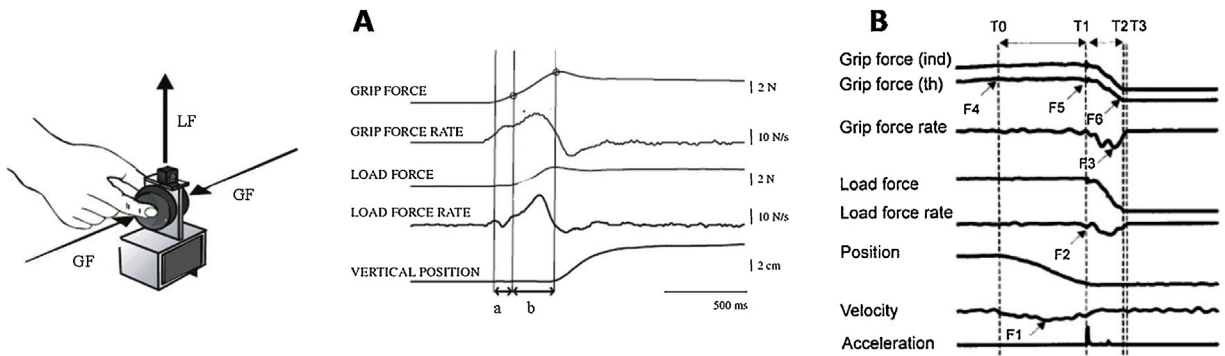


Fig. 1. On the left, the grip and load forces applied on a handheld object during a prehension task. (A) The precision grip variables are shown during a grip and lift task for a healthy subject in the middle of the Figure. The grip force (GF) is increasing first (preloading phase – a), followed by a parallel increase of GF and LF (loading phase – b). (B) The corresponding precision grip variables for a healthy subject during the release of a handheld object with T0–T1, the replacement phase, T1–T2 the rapid decrease of grip and load forces and T2–T3 the remove of the two digits. Adapted from Raghavan, Krakauer, and Gordon (2006) and Eliasson and Gordon (2000).

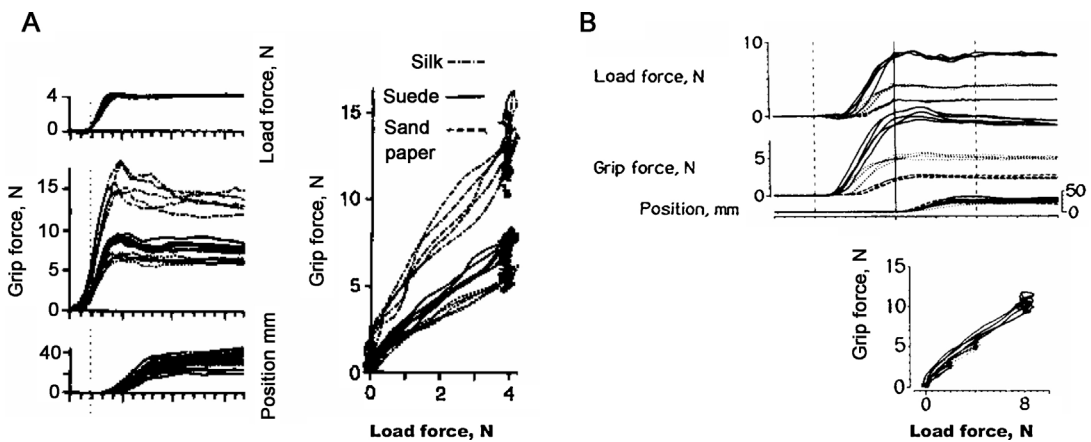


Fig. 2. The adaptation of the GF-LF coupling to different contact surfaces (silk, suede or sandpaper) (A) and to 3 different loads (B) in a healthy subject. Adapted from Johansson and Westling (1984) (A) and Johansson and Westling (1988) (B).

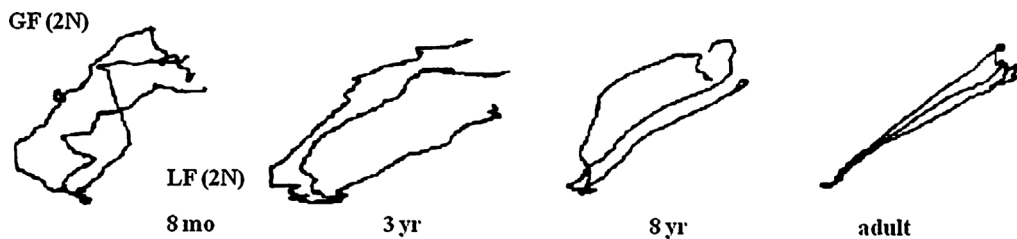


Fig. 3. The adaptation of the GF-LF coupling with age. Adapted from Forssberg et al. (1991).

held in the other hand (Islam et al., 2011) as well as pulling two pieces of a hand-held object apart (Smits-Engelsman et al., 2011). In both conditions healthy subjects showed well-timed and coordinated actions of both hands.

When one hand is used to induce a brisk increase of LF to an object held by the opposite hand, an anticipatory increase in GF precedes the LF increase (Bleyenheuft, Lefèvre, & Thonnard, 2009; Eliasson et al., 1995). After the brisk LF increase, a second increase in GF is observed. The temporal and dynamic characteristics of self-induced brisk load increases also develop with age, not reaching adults values before 9–10 years of age (Bleyenheuft & Thonnard, 2010b; Eliasson et al., 1995).

1.2. Sensory function

Tactile sensations have been classified into complex stimuli (texture, spatial acuity/orientation, size/shape/form, manual exploration) or simple stimuli (touch detection/vibration; Jones & Lederman, 2006). In children with typical development,

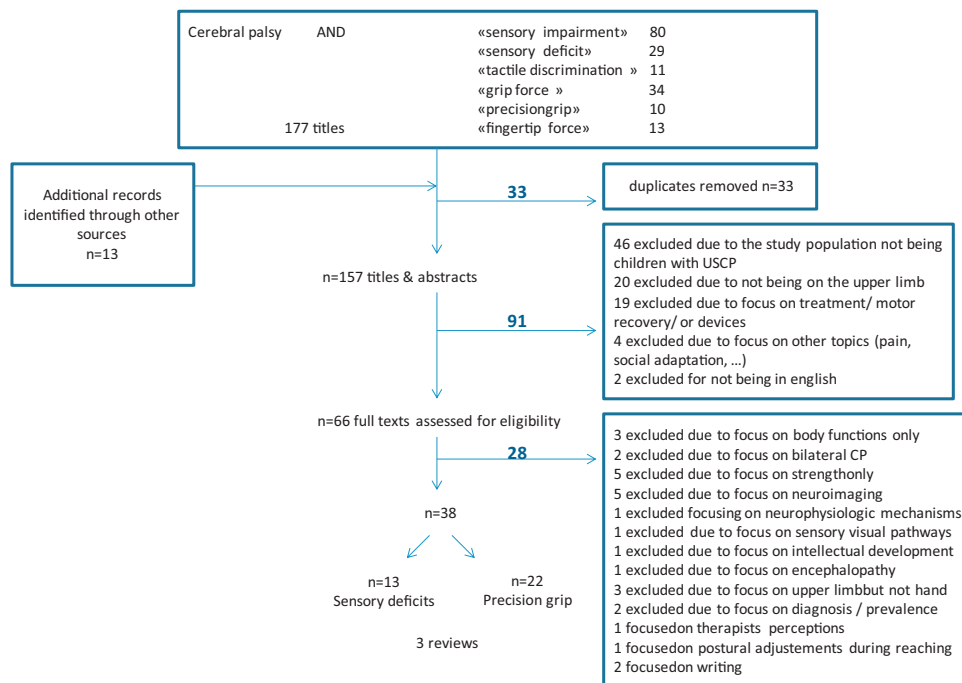


Fig. 4. flow diagram of the systematic research.

complex stimuli have been studied for spatial orientation and shape/form discrimination showing some improvements with age, reaching adult values after the first decade of life (Benton, Hamsher, Varney, & Spreen, 1983; Bleyenheuft, Cols, Arnould, & Thonnard, 2006; for a review see Bleyenheuft & Thonnard, 2009). Simple stimuli (sensitivity to pressure and vibration) have never been systematically investigated during childhood (Bleyenheuft & Thonnard, 2009). In children with HCP, four sensory modalities are frequently tested and impaired: tactile perception (sensitivity to pressure, simple stimulus) and 3 complex stimuli – tactile discrimination (spatial discrimination), stereognosis (form/shape recognition) and proprioception (Krumlinde-Sundholm & Eliasson, 2002).

2. Methods

2.1. Data sources and literature selection

A literature search was conducted on sensory and motor deficits of individuals with HCP using Pubmed and Scopus electronic databases. This search was performed inputting combinations of the following words: sensory impairment, sensory deficit, tactile discrimination, grip force, fingertip force and precision grip with “cerebral palsy”. Studies from 1990 to 2012 were retained. Additionally, a hand-search was performed in the reference lists of the articles meeting the search criteria. The search procedure ended in December 2012 and included only studies in English. We excluded studies that focused on heat and pain sensation, animal studies and papers that focused only on other types of CP (e.g. diplegic or bilateral CP) or on effects of treatments. We choose to exclude papers focused on other forms of CP (diplegia or quadriplegia) because their very low number and their small sample size (2 studies focused on bilateral CP only) was insufficient to draw conclusions. The flow diagram of the systematic search is presented in Fig. 4.

3. Results

As presented in the flow diagram (Fig. 4), 190 studies were detected through the systematic search, among which 38 were finally included in the systematic part of this review. Thirteen were research articles dedicated to sensory deficits (Table 1), 22 were research articles dedicated to precision grip (Table 2) and 3 were review papers. All the papers concentrated on children and adolescents (between 4 and 20 years old). Classifications such as gross motor function classification system (GMFCS, Palisano et al., 1997) or manual ability classification system (MACS, Krumlinde-Sundholm & Eliasson, 2003), allowing a quick description of patients motor abilities were not systematically used to describe the population and were therefore not included in the parameters of the tables. The same observation can be made for the clinical description including spasticity, range of motion and strength, which were not systematically documented. Over the 13 research papers dedicated to sensory deficits, 7 included only children with HCP, 5 included children with HCP and other forms of CP (data of

Table 1
Systematic review of sensory impairments.

Authors and year	Age (years)	Number	Topic	Measurements	Main findings
Van Heest et al. (1993)		40	Sensibility deficiencies	Stereognosis 2PD proprioception	Stereognosis affected in 97% of paretic limbs 2PD affected in 90% of paretic limbs Proprioception affected in 46% of paretic limbs
Lesný et al. (1993)		86	Sensory disorders	2PD	Decreased in all patients
Yekutieli et al. (1994)	6–17	8	Measuring sensory deficits in the hands	Stereognosis 2 PD	Impairments in stereognosis and 2PD
Cooper et al. (1995)	4–19	9	Determination of sensory deficits	Somatosensory potentials stereognosis proprioception	Bilateral sensory deficits sensory deficits did not mirror motor deficits somatosensory deficits related to motor function
Krumlinde-Sundholm and Eliasson (2002)	5–18	25	Relevance of tactile Sensibility tests for children with HCP	Light touch (SWM) 2 PD stereognosis functional sensibility	Useful: 2PD of 3 mm, stereognosis of objects and functional sensibility Less useful: SWM, stereognosis of forms deficient sensibility strongly related to dexterity
Arnould et al. (2007)	6–15	50	Hand impairments and relationship with manual ability	Light touch (SWM) stereognosis proprioception	Light touch and proprioception not related to manual ability stereognosis moderately related
Wingert et al. (2008)	13.9 (±5.2)	17	Tactile sensory abilities	Object recognition (shapes, common objects, capital letters) tactile roughness (gratings)	Impairment of objects recognition (3 tests) on the paretic hand Slight impairment in letters recognition on the non-paretic hand less accuracy in roughness discrimination
Law et al. (2008)	Mean 10.04	9	Correlation of deformity, spasticity, motor control, and sensation to hand function	Stereognosis, 2PD FIM, Melbourne assessment Functional hand grip test	Moderate correlation of sensory deficits with hand function
Kinnucan et al. (2010)	6–16	34	Correlation of stereognosis and motor function	Stereognosis Jebsen–Taylor motor test	Stereognosis impairment correlated with motor deficit
Klingels et al. (2010)	5–15	30	Reliability of sensory impairment measure	Light touch proprioception 2PD stereognosis	High reliability of the 4 sensory modalities tested
Bleyenheuft and Thonnard, 2011	10–16	12	Link between tactile spatial Discrimination and dexterity	Grating orientation task Digital dexterity (purdue pegboard test)	No correlation between tactile spatial resolution and digital dexterity when considering age-corrected data
Auld, Boyd, et al. (2012)	8–17	52	Impact of tactile dysfunction on motor abilities	Light touch (SWM) single point localization, double simultaneous static and moving 2PD stereognosis, texture	Tactile registration and tests of spatial perception moderately related to motor abilities
Auld, Ware, et al. (2012)	8–17	52	Reproducibility of tactile assessments	Light touch (SWM) single point localization, double simultaneous static and moving 2PD stereognosis, texture	Test–retest reliability for light touch and unilateral tests spatial perception learning effect for double simultaneous and tactile texture perception Recommend: SWM, single-point location static and moving 2 points

2PD, two point discrimination.

Table 2
Systematic review of precision grip.

Authors	Age, years	Number	Control subjects	Topic	Measurements/task	Main findings	
						More affected hand	Less-affected hand
Eliasson et al. (1991)	6–8	6	Yes	Coordination of forces	GF/LF coordination in grasp and lift of an object	Negative LF before lift sequential initiation of forces ↑ GF during negative LF ↑ preload duration ↑ and earlier peak of Gfrate ↑ and multiple GF peak	
Eliasson et al. (1992)	6–8	6	Yes	Anticipatory control	GF/LF coordination in grasp and lift of objects with varying weight	Sequential initiation of forces no influence of weight on GF and LF peaks and rates ↑ loading phase duration to reach higher LF and peak GF in heavier obj. later GF peak (in transition and static) large inter-individual variation static phase: adjustment of GF to weight	
Eliasson et al. (1995)	6–8	6	Yes	Anticipatory control	GF/LF coordination in grasp and lift of objects with varying contact surfaces	↑ GF/LF ratio in static phase higher and variable SM GF but not LF influenced by friction adaptation to friction in series of identical contact surfaces adaptation lost if random presentation of different contact surfaces	
Steenbergen et al. (1998)	14–18	14		Timing of prehension	Time to contact and time in contact during grasping objects of varying weight with varying time constraints	Time to contact: longer than in NP time to contact ↓ when heavy ↑ time in contact before lifting time in contact ↑ when heavy more than in NP hand decrease in duration over trials difference between hands ↑ with a timing constraint (as fast as possible)	Time in contact ↑ when heavy
Forssberg et al. (1999)	4–10	13		Impaired grip-lift synergy	Grip-lift synergy during an object lift correlation with clinics/MRI	7 children with impairment in grip-lift/6 without correlation with clinics correlation of GL synergy with total extent of lesions	11 out of 13 well coordinated synergy No correlation with clinics No correlation with MRI
Gordon and Duff (1999a)	8–14	15	Yes	Anticipatory scaling	GF/LF coordination in grasp and lift of objects with varying weight and contact surfaces (numerous trials)	Anticipatory control of object's weight: higher Lfrate for heavier object (>trial 20) Lower Lfrate than controls anticipatory control of object's texture: weak control after considerable practice	

Table 2 (Continued)

Authors	Age, years	Number	Control subjects	Topic	Measurements/task	Main findings	
						More affected hand	Less-affected hand
Gordon et al. (1999)	8–14	14	Yes	Bilateral coordination	GF/LF coordination in grasp and lift of objects with varying weight	<p>↑ duration of contact finger, preload phase, loading phase</p> <p>↑ GF at LF onset</p> <p>↑ minimum LF</p> <p>Multiple increments in force rates</p>	<p>Subtle impairments</p> <p>↑ duration of contact finger, preload phase, loading phase</p> <p>↑ minimum LF</p> <p>Anticipatory control preserved</p>
Gordon and Duff (1999b)	8–14	15	Yes	Relationship prehension clinical measures	GF temporal and dynamic variables/correlation with clinical measures	<p>Transfer of information from NP to P hand</p> <p>static GF correlates with sensory deficits and with spasticity level</p> <p>GF rate scaling related to 2PD and pinch strength</p> <p>variability in preload phase duration related to pressure sensitivity and spasticity</p>	
Eliasson and Gordon (2000)	7–13	14	Yes	Object release	GF/LF coordination in object release Forces and temporality	<p>↓ replacement phase, ↑ release phase and finger difference</p> <p>peak velocity just before contact</p> <p>high LF rate at contact</p>	
Gordon et al. (2003)	7–14	15	Yes	Object release on stable and unstable surface	GF/LF coordination in object release Forces and temporality with varying accuracy and speed	<p>↑ duration of replacement, release and digit remove phases</p> <p>↑ 3 phases when accuracy ↑</p> <p>↑ variation of the 3 phases duration</p> <p>↓ velocity</p> <p>If speed ↑: ↓ duration release, finger ≠</p> <p>If speed and accuracy ↑: ↑ duration for 3 phases</p>	<p>↑ duration of replacement and release phase</p> <p>↑ variability of replacement time and velocity</p>
Duff and Gordon (2003)	7–14	18	Yes	Grasp control	Forces adaptation to familiar and novel objects of varying weight	<p>Familiar objects: adaptation of LF and LF rate from the first lifts/anticipatory control</p> <p>Novel objects: possible forces scaling adapted to ≠ weights after extended practice</p>	
Duque et al. (2003)	8–19	16	Yes	Relation grasp/corticospinal dysgenesis	GF/LF coordination GF and LF rate peaks time shift Functional measurement Peduncular symmetry	<p>↑ duration of contact finger, preload phase, loading phase</p> <p>Multiple increments in force rates</p> <p>↑ time-shift between force rate peaks</p> <p>peduncular symmetry correlated to</p> <p>↑ preload phase and time-shift</p>	<p>↑ duration of contact finger</p>
Steenbergen et al. (2004)	13–19	11		Grip selection	Varying constraints in a pick and pointing task with a pencil time of max comfort	<p>Postural comfort at the start ≠ between left and right hemiparesis</p> <p>Left brain damage: deficits in forward movement planning</p>	<p>Postural comfort at the end</p>

Gordon et al. (2006)	4–14	8		Forces planning during grasp transfer of information between both hands	Forces adaptation to objects of varying weight with transfer from one to the other hand	No adaptation of Lfrate for consecutive lifts with ≠ weights Lfrate adapted for heavier weight after transfer from the non-involved	Adaptation of Lfrate for consecutive lifts with ≠ weights Lfrate adapted for heavier weight after transfer from the involved
Mutsaerts et al. (2006)	15–19	11		Anticipatory planning deficits and tasks context	Choice of different grasping patterns following the context		Anticipatory planning deficit due to deficit in motor imagery
Eliasson et al. (2006)	5 to adult	5		Longitudinal follow-up of precision grip		With time: ↓ overall grip-lift task duration ↓ preload phase duration ↓ loading phase variation ↓ of pushing down the object before lift ↓ of GF at LF onset	
Steenbergen et al. (2008)	4–13	7		Force control during bimanual lifting	Temporal and force analysis of lift and release of an object in unimanual or bimanual conditions with varying weight	Bimanual lift facilitates adequate forces adaptation for GF at LF onset and peak GF rate	Bimanual lift: ↑ duration of all phases; adaptation of GF at LF onset and peak Gfrate toward the involved hand
Mackenzie et al. (2009)	Mean 11.6	6	Yes	Force coordination in unimanual and bimanual tasks	GF and LF in static and dynamic conditions in unimanual, bimanual liftings and oscillations	Unimanual: ↑ GF/LF in hold and drop bimanual: no difference with unimanual irregular LF profiles	Bimanual: no difference with unimanual
Bleyenheuft and Thonnard (2010a, 2010b)	10–16	12	Yes	Predictive and reactive control of precision grip	GF and LF temporal and dynamic profile during brisk load increase in predictable and unpredictable conditions correlation with CS tract dysgenesis	Dynamic variables: no significant ≠ Temporal: deficits after brisk increase predictable condition: ↑ and more variable delay to reach max GF, ↑ delay post-impact Unpredictable condition: ↑ delay post-impact	No significant ↑ with controls
Smits-Engelsman et al. (2011)	5–14	12		Bimanual force coordination	GF and LF temporal and dynamic profiles in a bimanual task of object dissociation	Adaptation of force levels to pull objects apart following electromagnet settings Impairments on all forces coordination variables Impairments not related to the position of the hands ↑ synchronization of forces when more force needed to separate the 2 units	

Table 2 (Continued)

Authors	Age, years	Number	Control subjects	Topic	Measurements/task	Main findings	
						More affected hand	Less-affected hand
Islam et al. (2011)	9–20	12		Grip force coordination during bimanual tasks	GF and LF temporal and dynamic profiles in a bimanual task of object superposition	Temporal control is disrupted, whatever the hand used (reversed coordination) ↑ Preparation phase duration ↑ disturbance in anticipation when the non-involved is the holding hand smaller holding hand GF in preparation and transition phases/smaller GF ↑	
Prabhu et al. (2011)	5–10	11		Grip force coordination during walking	GF/LF parallel evolution: cross-correlation time-lag, GF/LF ratio	No parallel oscillation of GF to adapt to changing LF in the more affected hand	Sinusoidal adaptation of GF parallel to LF changes

Abbreviations: G, Grip force; LFlod, force; 2PD, two point discrimination; NP, non-paretic.

children with HCP were presented separately). For precision grip, over the 22 papers included, only 3 included other forms of CP in addition to hemiplegia. In both Tables, number of patients reported refers to number of HCP patients included.

3.1. Sensory dysfunction

The measurement of sensory dysfunction is considered crucial in individuals with HCP because of the frequency of this dysfunction (Arnould, Penta, & Thonnard, 2007; Auld, Boyd, Moseley, Ware, & Johnston, 2012; Auld, Ware, Boyd, Moseley, & Johnston, 2012; Bleyenheuft & Thonnard, 2011; Cooper, Majnemer, Rosenblatt, & Birnbaum, 1995; Klingels et al., 2010; Krumlinde-Sundholm & Eliasson, 2002; Law et al., 2008; Kinnucan, Van Heest, & Tomhave, 2010; Lesný, Stehlík, Tomásek, Tománková, & Havlíček, 1993; Van Heest, House, & Putnam, 1993; Wingert, Burton, Sinclair, Brunstrom, & Damiano, 2008; Yekutieli, Jariwala, & Stretch, 1994), affecting up to 90% of the children. Table 1 reports the result of the systematic search on sensory deficits in children with HCP. Overall, the four sensory modalities mainly tested in children with HCP – tactile perception (light touch), tactile discrimination, stereognosis and proprioception – are frequently impaired in HCP (Krumlinde-Sundholm & Eliasson, 2002). Stereognosis is described as affected in 10 of the papers selected (Arnould et al., 2007; Auld, Boyd, et al., 2012; Auld, Ware, et al., 2012; Cooper et al., 1995; Klingels et al., 2010; Krumlinde-Sundholm & Eliasson, 2002; Law et al., 2008; Kinnucan et al., 2010; Van Heest et al., 1993; Wingert et al., 2008; Yekutieli et al., 1994). Spatial discrimination is described as impaired in all the selected papers but 2 (Arnould et al., 2007; Auld, Boyd, et al., 2012; Auld, Ware, et al., 2012; Bleyenheuft & Thonnard, 2011; Klingels et al., 2010; Krumlinde-Sundholm & Eliasson, 2002; Law et al., 2008; Lesný et al., 1993; Van Heest et al., 1993; Wingert et al., 2008; Yekutieli et al., 1994). Proprioception was measured and shown to be affected in 4 of the papers (Arnould et al., 2007; Cooper et al., 1995; Klingels et al., 2010; Van Heest et al., 1993). Finally tactile perception was shown affected in the 5 papers that were including it (Arnould et al., 2007; Auld, Boyd, et al., 2012; Auld, Ware, et al., 2012; Klingels et al., 2010; Krumlinde-Sundholm & Eliasson, 2002). Sensory deficits are thus frequent but probably often underestimated by classical clinical examinations in these children (Cooper et al., 1995).

The selected papers of this section follow a rigorous design. However only a few include large cohorts of subjects (Arnould et al., 2007; Auld, Boyd, et al., 2012; Auld, Ware, et al., 2012; Lesný et al., 1993). Until recently sensory testing of children with HCP was not multimodal. Recent papers have provided good advances both for multimodality and reliability of sensory assessments (Auld, Boyd, et al., 2012; Auld, Ware, et al., 2012; Klingels et al., 2010). However, it is important to note that the reliability of an instrument is not related to the relevance of the sensory modality tested by this instrument for prehension. Furthermore, many of the papers cited fail to report age-corrected results. Since these studies often include children with HCP from 4 to 5 years up to 17–18 years of age, many of the sensory and motor tests used are likely to evolve with age.

3.2. Precision grip

Table 2 summarizes the precision grip deficits in children with HCP. In the more affected hand, the grip-lift movement is characterized by an asynchronous onset of grip and load forces, by multiple successive increments in grip and tangential force rates (i.e. force derivatives) and by excessive grip forces, especially at the onset of LF increase (Duque et al., 2003; Eliasson et al., 1991, 1992, 1995a; Forssberg et al., 1999; Gordon & Duff, 1999a, 1999b; Gordon et al., 1999; Steenbergen, Hulstijn, de Vries, & Berger, 1996). A maladaptive strategy in the load force is also observed since the children with HCP frequently push the hand-held object down against the table before lifting it (Eliasson et al., 1991, 1992). These deficits do not increase with age (Eliasson, Forssberg, Hung, & Gordon, 2006) which is in agreement with other findings on maximal grip strength and changes in isometric finger forces (Eliasson & Gordon, 2000). Some of these impairments are correlated with clinical measures (Gordon & Duff, 1999a, 1999b). When children with HCP are asked to release an object, their force coordination is also sequential but can be scaled to the weight of the object (Eliasson & Gordon, 2000). These object release and replacement impairments increase under conditions of imposed speed and accuracy (Gordon, Lewis, Eliasson, & Duff, 2003).

The mechanisms underlying fine prehension impairments have been studied in many studies to tentatively link the deficits observed with either inefficient feedback from the paretic hand (Gordon & Duff, 1999a, 1999b; Gordon et al., 1999) and/or to high-level deficits in sensorimotor integration (Eliasson et al., 1992; Gordon, Charles, & Steenbergen, 2006). While initial studies of planning suggested an inability to develop predictive control in grasp (Eliasson et al., 1991, 1992), predictive abilities (notably to adapt fingertip forces to different weight and friction conditions) were demonstrated subsequently as partially remedied when children with HCP are provided extensive practice (Duff & Gordon, 2003; Gordon & Duff, 1999a). In these conditions, they are able to form and retain internal representations even for new objects (Duff & Gordon, 2003). The respective contribution of feedforward and/or feedback control in the impaired precision grip of children with HCP has been further assessed using a paradigm (self- or-examiner-imposed load to a handheld object) where both predictive and reactive control were tested separately (Bleyenheuft & Thonnard, 2010a). Deficits were observed both in predictive and reactive conditions in the more affected hand whereas no deficits were evidenced in the less affected hand. Children with HCP presented an ability to anticipate events prior to brisk load increase in the more affected hand, but were unable to pursue predictive control after load increase. Planning deficits in both hands were further studied in bimanual protocols. An influence of bimanual tasks on the performance of the more affected and less affected hand has been observed (Steenbergen, Charles, & Gordon, 2008), suggesting that these children have the ability to transfer motor programs from the less affected to the more affected hand (Gordon et al., 1999, 2006).

In summary, these studies demonstrated that predictive abilities, like motor imagery (Steenbergen & Gordon, 2006), are present in children with HCP (Mutsaerts, Steenbergen, & Bekkering, 2006), but clearly impaired. Even if some differences have been observed following the left or right side of the lesion (Steenbergen, Meulenbroek, & Rosenbaum, 2004), it has been generally suggested the impaired precision grip of children with HCP is the consequence of an inability to use internal models of manipulated objects.

Some of these precision grip impairments, considered as indicators of motor planning impairments were strongly correlated with corticospinal tract dysgenesis as estimated by diffusion tensor imaging (Bleyenheuft and Thonnard, 2010a) or by conventional MRI (Bleyenheuft and Thonnard, 2010a, 2010b; Duque et al., 2003). As corticospinal tract dysgenesis was also correlated with clinical tests of stereognosis, dexterity and activities of daily living (Bleyenheuft, Grandin, Cosnard, Olivier, & Thonnard, 2007), CS tract integrity may provide a useful prognostic tool for predicting upper-limb deficits and their motoric consequences, while prehension is still developing (Bleyenheuft et al., 2007; Duque et al., 2003).

The less affected hand, that is not systematically investigated, also presents subtle deficits (Duque et al., 2003; Forssberg et al., 1999; Gordon et al., 1999, 2003; Mutsaerts et al., 2006; Steenbergen, Hulstijn, Lemmens, & Meulenbroek, 1998). However, anticipatory adjustments are present, showing predictive abilities in this hand (Bleyenheuft & Thonnard, 2010a; Gordon et al., 1999, 2006). This very intriguing lateralized impairments in motor planning have been recently explained as reflecting a lateralized impairment in the sensorimotor integration (Prabhu, Diermayr, Gysin, & Gordon, 2011). Interestingly it was also observed that children with HCP present less accurate performance during bimanual tasks in both the more and less affected hand (Islam et al., 2011; Smits-Engelsman et al., 2011), suggesting that while sensorimotor integration seems to lateralize, performance of each effector can be influenced by the other.

It should be noted that the precision grip studies of children with HCP presented in this section were generally conducted on small samples of subjects (<20) and compared to age-matched controls. Only one longitudinal follow-up was reported (Eliasson et al., 2006). The age range of the studies presented in this section is similar to the range observed for sensory deficits: from 4 to 20 years old. Since precision grip is not considered mature before 6 to 8 years of age (Forssberg et al., 1991) and in some tasks does not even reach adults values before 9–10 years of age (Bleyenheuft & Thonnard, 2010b; Eliasson et al., 1995), development could have interfered with the results. However, since most studies involved an age-matched control group and did not correlate values with other assessments likely to evolve with age, development is not likely (exclusively) responsible for the results obtained. The relationship between these precision grip deficits and specific neural damage and re-organization has been described in a recent review (Gordon, Bleyenheuft, & Steenbergen, *in press*).

3.3. *Link between the sensory abilities and the precision grip*

The link between sensory impairments and prehension deficits is first described on the basis of the papers included in the “sensory dysfunction” section and then in the “precision grip” section.

From the papers selected in the “sensory dysfunction section” (Table 1), the relationship between sensory deficits and motor abilities is not straightforward in children with HCP. While a relationship is clearly established between stereognosis and motor function (Arnould et al., 2007; Auld, Boyd, et al., 2012; Cooper et al., 1995; Krumlinde-Sundholm & Eliasson, 2002; Kinnucan et al., 2010; Law et al., 2008) conflicting results are reported for the other modalities (Arnould et al., 2007; Auld, Boyd, et al., 2012; Bleyenheuft & Thonnard, 2011; Cooper et al., 1995; Krumlinde-Sundholm & Eliasson, 2002; Law et al., 2008). These conflicting results could be due to the absence of age correction in the data. Even in healthy controls, a strong relationship can be erroneously observed between sensory and motor abilities in children between 4 and 17 years old (Bleyenheuft, Wilmotte, & Thonnard, 2010). When data are corrected for age, no relationship can be observed. The effect of age, present in both modalities, is exclusively responsible for the relationship initially (and falsely) detected. Therefore, it is urgent for clinical practice and research to provide developmental normative data for both sensory and motor assessments and to use age-corrected data.

In precision grip tasks, the ability to adapt the forces to different weight and friction conditions during lift phase clearly shows that the forces are modulated based on sensory feedback regarding object mass and friction (Duff & Gordon, 2003; Gordon & Duff, 1999a, 1999b). However, unlike healthy children of the same age, the adaptations to these different conditions during the first part (i.e. the lift phase) of object manipulation are only possible through extensive practice (Duff & Gordon, 2003; Gordon & Duff, 1999a, 1999b) showing an alteration of sensorimotor integration. Therefore, in everyday life, while a quick adaptation to familiar objects is observed (Duff & Gordon, 2003), during manipulation of new objects, the sensory information is probably less taken into account in their precision grip processing than control subjects. Furthermore, as described in the precision grip section, these deficits in sensorimotor integration related to anticipatory control during the lift of an object can be remediated (at least partly) by transferring information from the less affected to the more affected hand (Gordon et al., 1999; Gordon et al., 2006; Steenbergen et al., 2008).

Altogether, these results show that the sensory abilities and especially the sensorimotor integration of children with HCP are affected and do have an influence on precision grip. With a better sensorimotor integration (due to many trials or inputs from the less-affected hand), anticipatory control of precision grip is improved. This leads to the question of the training not directly of the sensory abilities, but more of the sensorimotor integration in neurorehabilitation for these patients.

4. Discussion – implications for rehabilitation

The study of precision grip, leading to a better understanding of motor control in children with HCP, has already provided major insights into neurorehabilitation. Notably, the finding that planning impairments can be partially remedied when children with HCP are provided extensive practice (Duff & Gordon, 2003; Gordon & Duff, 1999b) led at least one research group to consider constraint-induced movement therapy (CIMT, initially developed for stroke patients) as a model for providing extensive task-related practice (Charles, Lavinder, & Gordon, 2001; Charles, Wolf, Schneider, & Gordon, 2006; Gordon, 2011). CIMT is now a widely spread neurorehabilitation modality offering opportunities to improve functional abilities of the more affected hand (Eliasson & Gordon, 2008; Gordon & Friel, 2009; Gordon, 2011; Sakzewski, Ziviani, & Boyd, 2009).

A second clinical application was highlighted following the findings linked to the possibilities of information transfer from one hand to the other. Gordon et al. showed in 1999 immediate transfer from the less affected to more affected. This suggested the problem in the more affected hand was the impaired sensation (inability to use sensory information to form internal model). However, a subsequent study tested this hypothesis, and despite lack of planning in the more affected hand, children could extract sufficient weight-related information for subsequent transfer to lifts with the less-affected hand (Gordon et al., 2006). This suggested that it was the ability to integrate sensory information and motor commands from the affected hand that was impaired (sensorimotor integration). Subsequent work showed that like in reaching tasks (Steenbergen et al., 1996), simultaneous grasp of two objects resulted in improved performance of the more affected hand (Steenbergen et al., 2008). These studies suggest the less affected hand could provide a template for improving motor performance of the more affected hand, and provides a strong rationale for the development of bimanual training approaches (HABIT; Gordon et al., 2008; Gordon, Schneider, Chinnan, & Charles, 2007).

This review further supports the use of bimanual training not only because of the potential transfer of a motor plan, but also because children with HCP have shown less accurate performance during bimanual precision grip tasks, even in the less affected hand (Islam et al., 2011; Smits-Engelsman et al., 2011). As bimanual activities are needed in activities of daily life, there is a real need to train impaired bimanual coordination.

Additional implications for rehabilitation could arise from the results of the above studies on precision grip deficits in children with HCP in the future. First, in children with HCP, the precision grip analysis showed that the less affected hand has only subtle deficits. *Therefore the performance of this less affected hand is of interest for rehabilitation purposes.* As the subjects are able to correctly program precision tasks with the less affected hand, this ability could be used either to construct a template for the appropriate motor command (like in HABIT, Gordon et al., 2007, 2008; Hung, Charles, & Gordon, 2004) or to transfer intact sensory information from the less affected to the more affected hand. While the transfer of information from the less affected to the more affected hand has been clearly demonstrated (Gordon et al., 2006), a neurorehabilitation based on the alternate use of both hands, starting with the less affected has not yet been tested. While a neurorehabilitation strategy based on this principle could be interesting if it enables acquisition of a vivid motor plan that could be transferred from the less affected to the more affected hand, the effectiveness of this scheme could be questioned because of inter-hemispheric influences (Mochizuki, Huang, & Rothwell, 2004; Rouiller et al., 1994). Through transcallosal interactions, each primary motor cortex when stimulated has an inhibitory action on the opposite motor cortex. Future studies testing these hypotheses should provide interesting clues on the possibility of transfer from the less affected to the more affected hand (Duque et al., 2005; Ward & Cohen, 2004).

Second, the sensory impairment highlighted in this review and their potential consequences on the precision grip of children with HCP raise the question of a sensory training. Sensory abilities are needed for precision grip tasks and are traditionally considered a prerequisite for the performance of prehension tasks (Gordon et al., 1999; Jones, 1996; Moberg, 1958). This implies a strong link between sensory and motor functions that can be questioned as a result of the conflicting results of a relation between sensory dysfunction and motor deficits. To date, many types of training have provided evidence of increasing precision grip performance in children with HCP: short term training effects were reported (Steenbergen et al., 2008), training based on visual feedback (Valvano & Newell, 1998), and intensive training with CIMT (Charles et al., 2001; see also Gordon & Friel, 2009; Sakzewski et al., 2009). However, the potential sensory training induced by these therapies has never been investigated. On the basis of the many sensory deficits identified in this review and their potential importance in the grasping of children with HCP, we suggest: (1) the systematic documentation of sensory deficits before and after intensive training processes, (2) the introduction and testing of specific sensory stimulations during intensive interventions.

Several gaps in knowledge were observed as a result of this systematic review. First, since many studies were performed before the existence or common reporting of functional ability (e.g. MACS, GMFCS), it is not known how sensory and precision grip impairments affect function. Also, nearly all studies of precision grip in cerebral palsy were in individuals with hemiplegia. Although this subtype of CP is among the most common, overall hand function remains high (generally MACS level I or II) because the contralateral hand is largely spared. Thus future work should focus on other subtypes of CP. Finally, the oldest participants in these studies were in their late adolescence. Although precision grip does improve from childhood to adolescence (Eliasson et al., 2006), little is known about hand function in adults with CP. It would be interesting to compare these individuals with adults with acquired hemiplegia due to stroke to study mechanisms of early versus late plasticity.

5. Conclusion

In this manuscript, we showed that the four sensory modalities mainly tested are frequently impaired in HCP. Sensory deficits are thus frequent and probably often underestimated using standard clinical examination. These deficits in sensory function have been suggested to underlie the basis of impairments in predictive motor control of individuals with HCP. The ability to use such information in an anticipatory manner (i.e. based on memory from prior manipulations) to scale their forces was present in children with HCP. They were able – often with many trials – to predictively scale their forces to different weights or surface friction. Therefore, there is still an ability to use predictive control, even if it is impaired in the more affected hand. It is suggested that the less affected hand may aid the subsequent control of the contralesional hand. Indeed, even if it has subtle deficits, this hand has proven an intact ability to aid in anticipatory control. In addition, we strongly recommend a systematic documentation of the sensory deficits before and after intensive training, with age-corrected results. This could document potential changes in sensory functions due to the training and open the door to introduce systematic sensory training in intensive rehabilitation.

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