Lack of Predictive Control in Lifting Series of Virtual Objects by Individuals With Diplegic Cerebral Palsy

Firas Mawase, Simona Bar-Haim, and Amir Karniel, *Senior Member, IEEE*

***Abstract*—To date, research on the motor control of hand function in cerebral palsy has focused on children with hemiplegia, although many persons with diplegic cerebral palsy (dCP) have asymmetrically decreased hand function. We explored the predictive capabilities of the motor system in a simple motor task of lifting a series of virtual objects for five persons with spastic dCP and five age-matched controls. When a person lifts an object, s/he uses an expectation of the weight of the object to generate a motor command. We asked the study subjects to lift a series of increasing weights and determined whether they extrapolated from past experience to predict the next weight in the series, even though that weight had never been experienced. Planning of precision grasp was assessed by measurement of the grip force at the beginning of the lifting task and by estimating the motor command. Execution of precision grasp was assessed by measurement of the time interval between the onset of grip and the onset of movement. We found that persons with dCP demonstrated a lack of predictive feed-forward control in their lifting movements: they exhibited a significantly longer time between onset of grip and onset of movement than the control subjects and they did not predict the weight of the next object in the lifting task. In addition, for subjects with dCP, the time between the onset of grip and the onset of movement of the dominant hand correlated strongly with the outcome of a hand function test. We postulate that a higher-order motor planning deficit in addition to execution deficit are evident in the subjects with spastic diplegic.**

***Index Terms*—Diplegic cerebral palsy, grip force, motor control, predictive control.**

I. Introduction

THE TERM cerebral palsy (CP) is used to describe a group of disorders of the development of movement and posture that cause activity limitation; these disorders are attributed to nonprogressive disturbances that had occurred previously in the developing fetal or infant brain. The motor disorders of CP are often accompanied by disturbances of sensation, cognition, communication, perception, and/or behavior, and/or by seizure disorder [1]. The above definition emphasizes the fact that CP is not an etiological diagnosis, but a clinical descriptive term for a condition that is heterogeneous in etiology, expression and severity. It also stresses the idea of impairment in development (typical versus CP) being essential to the CP concept. Among the many causes of CP are prematurity, perinatal asphyxia, and deficiency in maternal iodine [2]. It is important to note here that the brain damage is permanent but not progressive.

Hemiplegic cerebral palsy (hCP) form has been defined as an involvement in one side of the body, with upper extremity generally more affected than the lower. In many cases, the cause is a focal traumatic, vascular, or infectious lesion. Most hemiplegic children walk independently by the age of three years. On the other hand, in diplegic cerebral palsy (dCP) the lower extremities are severely involved and the arms are mildly involved. Diplegia is becoming more common as more low-birth-weight babies survive. Hand dexterity and fine motor control are also impaired in dCP [3].

Traditionally studies in dCP, concentrated on movement impairments of the lower extremities (e.g., walking) which is severe while the hand function was considered mild. This is perhaps the reason that only very few studies have investigated the performance of hand function in dCP. Today is known that in dCP both nondominant and dominant hand showed sensory impairments. Observed deficits consist identifying shapes, common objects, or two points discrimination [4]. Impairments in this population include difficulties in activities of daily living, deformities, spasticity, and motor control.

The diplegic form of CP has been defined also "as a condition of more or less symmetrical paresis of cerebral origin more severe in the lower limbs than the upper and dating from birth or shortly thereafter" [5]. Several factors may contribute to the impaired hand function in persons with diplegic CP, among them spasticity, distal weakness, impaired tactile sensibility, uncoordinated movements, and impaired motor control [5], [6]. In spastic dCP, movement impairment of the lower extremities is severe while that of the arms is mild. Eliasson *et al.* (2006) carried out a long-term (13-year) study of the development process underlying hand function in children with hemiplegic or diplegic CP; to test hand function, they used the timed-task Jebsen-Taylor test (JTT) of hand function, and they also evaluated temporal coordination of fingertip coordination. In the first data-collection session, both groups of subjects presented an impaired force-ratio path in terms of variability and straightness. At the end of the 13-year follow-up period, they found that in both hemiplegic and diplegic CP the improvement in hand function continues over a longer time frame than previously expected, regardless of the initial severity of the hand function [7].

Computational motor control is a growing field of study in which engineering concepts from control theory and other mathematical tools are used to quantitatively describe the neural con-

Manuscript received March 03, 2011; revised August 04, 2011; accepted September 25, 2011. Date of publication October 06, 2011; date of current version December 07, 2011. The study was supported in part by the United States—Israel Bi-National Science Foundation (BSF), Jerusalem, Israel and in part by the Israel Science Foundation (ISF), Israel.

F. Mawase and A. Karniel are with the Department of Biomedical Engineering, Ben-Gurion University of the Negev, 84105 Beer-Sheva, Israel (e-mail: mawasef@bgu.ac.il; akarniel@bgu.ac.il).

S. Bar-Haim is with the Faculty of Health Sciences, Ben-Gurion University of the Negev, 84105 Beer-Sheva, Israel (e-mail: adi-star@013.net).

Digital Object Identifier 10.1109/TNSRE.2011.2170589

trol of movement [8]. We believe that it is possible to apply concepts from computational motor control theory to the diagnosis and rehabilitation of arm movements in persons with dCP, as has been done recently for patients suffering from damage to the primary motor cortex [9]–[11]. Studies conducted to date indicate that upper-extremity weakness, spasticity, and abnormal motor synergies do not adequately explain the impairment in reaching movements and lifting tasks [10], [12]–[14] and suggest that additional higher-order control deficits may be present.

The feedback control mechanism has been used to describe the biological motor control system since the beginning of cybernetics as a modern science in the 1940s [15]. During fast movements, however, the feedback control mechanism is unable to correct a trajectory quickly and to generate a stable system, due to unavoidable delays in the nervous system. It has therefore been suggested that the brain employs internal feedforward models [16]–[18]. These models are neural mechanisms that can mimic the input/output characteristics—or their inverses—of the motor apparatus and of the external environment. Forward internal models can predict sensory consequences from efference copies of motor commands. Inverse internal models, in contrast, can calculate necessary feedforward motor commands from desired trajectory information [17], [19].

It has been shown that the motor system can adapt to external perturbations and, in that general sense, can generate internal representations of the external environment. Understanding the structure and capabilities of these internal representations is essential for understanding the motor system [20]–[22]. Several studies have examined adaptation to stochastic environments in neurologically intact subjects. These studies suggested that in a randomly varying environment, a short-time averaging process underlies the representation of the task in the motor working memory and that learning may not represent the statistics of how perturbation changes over a longer time scale [23]–[26]. On the other hand, in a lifting task, we found evidence supporting the hypothesis that the motor system can extrapolate and predict environments that were not experienced in the recent past or that do not represent an average of past experience in the case of predicting the succeeding weight that follows a series of increasing weights [20].

To study higher-order sensory-motor integration in hand motor control, Johansson evaluated the ability of subjects to predict grip forces when required to grasp and lift objects [27]. It has been suggested that predictive (feedforward) grip force control, which ensures the generation of appropriate grip and load forces to prevent the crushing of fragile objects or the dropping of heavy ones, is based on the structure of internal models of object properties in the central nervous system [28]–[33].

Several studies have investigated the relationship between motor commands and predictive control. Flanagan *et al.* (2003) suggested that in early stages of manipulating objects neurologically intact subjects could predict the consequences of their actions, as measured by the grip force they used to grasp the object [34]. Ben-Itzhak and Karniel (2008) suggested the minimum acceleration criterion with constraints (MACC) hypothesis that posits that the extracted value of the jerk (change in acceleration) at the beginning of the movement is a physiological interpretation of the motor command [35].

In experiments with a short series of objects with increasing weights, we have recently found that neurologically intact individuals are able to fit their grip forces at the onset of movement to the next object in the series. Since the grip force at fast movement onset represents the internal expectation, we concluded that this expectation is based, at least in part, on extrapolation and not solely on the average of past experience [20]. In children with hemiplegic CP, predictive grip force control for novel objects is impaired [36]–[39]. The deficit in predictive control is thought to result from an inability to form or access internal models of object properties due to disrupted sensory feedback (perceptive impairment) from the affected hand [37], [38], [40], and/or from higher-order impairment in sensory-motor integration [36].

There is strong evidence in the literature that movement and perception are two sides of the same coin [41], [42]. The theory of sensory integration states that perception is not just the acquisition of sensory information, but an active process aimed at guiding the execution of a correct movement, i.e., coherent with the motor program planned before the action [40].

The purposes of this study were to explore the limitation and origin of the deficits in predictive control of individuals with dCP by using our recently developed protocol for lifting a series of objects with increasing weights [20]. In order to do so, we analyzed a number of kinematic and dynamic parameters when the participants made grasping movements and also by finding out the relation between these parameters and the results of the hand function test.

II. METHODS

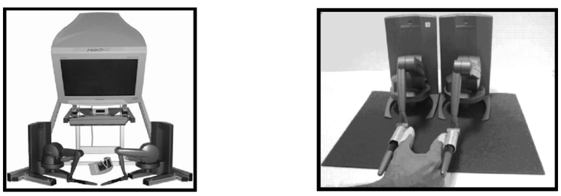
A. Participants and Study Setting

Five individuals with spastic dCP (two women and three men, aged 20–36 years, mean = 26.8) and an equal number of age- and gender-matched neurologically intact control subjects (aged 24–27 years, mean = 25.4) participated in the study after signing an informed consent form, as required by the local Helsinki Committee. All the control subjects are neurologically intact. Three CP subjects have mild dCP and can walk independently and the two others have moderate dCP and walk with crutches or get around in a wheelchair. All the subjects have a cognitive level that is adequate to enable them to comprehend and cooperate in treatment and testing. They were classified at levels I or II of the Manual Ability Classification System (MACS) for persons with CP. MACS was developed to classify into five levels how persons use their hands when handling objects in daily activities, according to the primary criterion that the distinctions in manual ability should be clinically meaningful [7]. The classification is designed to reflect the person's typical manual performance, not the patient's maximal capacity. It classifies what persons do when using one or both of their hands for activities, rather than assessing and classifying each hand separately. For four subjects, hand function of the dominant hand was assessed with the JTT [43]. JTT is a seven-task test that evaluates a broad range of everyday hand functions, i.e., writing, turning pages, picking

TABLE I
CHARACTERISTICS OF THE STUDY SUBJECTS WITH CEREBRAL PALSY

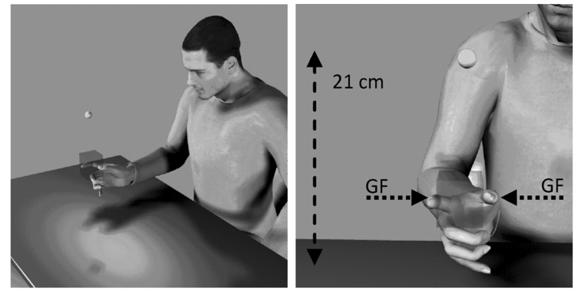
Subject number	Age (years)	Gender	Dominant Hand	MACS level	JTT (seconds)
1	23	Male	Right	I	5.24
2	36	Male	Right	II	10.66
3	20	Male	Right	I	16.83
4	33	Female	Right	II	9.11
5	22	Female	Right	I	Not available

MACS, Manual Ability Classification System; **JTT**, Jebsen-Taylor Hand Function Test; score represents the average time taken in seconds, using the dominant hand, to complete the seven tasks of the JTT

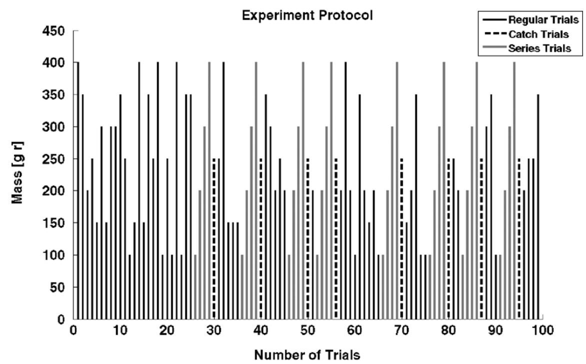


(a) (b)

Fig. 1. The virtual reality system. (a) The dual Reachin/Sensegraphics display system is based on two robotics devices and an augmented reality display that allows subjects to see and feel objects with both hands within a small workspace. (b) One thimble connects the index finger and another thumb to a robotic arm.



(a)



(b)

Fig. 2. The virtual object and Experimental protocol. (a) Illustration of the virtual object (transparent box), target point (circle), the configuration of the hand, wrist and fingers used to grasp it, and the grip forces produced during a single lifting movement. (b) Object weights selected randomly in each trial ranged between 100 and 400 g (black lines). A series of four trials with increasing weights of 100, 200, 300, 400 g (gray lines), followed by a catch trial of 250 g (black dashed lines), appeared randomly eight times during the experiment with no overlapping.

up small objects, feeding, stacking checkers, picking up large lightweight objects, and picking up large heavy objects. Patient characteristics are shown in Table I. All the subjects used only their dominant hand for the lifting and for the clinical measure of the hand function (JTT).

Therapists specializing in the treatment of CP in the Human Motion Analysis Laboratory, Assaf-Harofeh Medical Center, referred persons to the study. Only cerebral palsy persons who meet the requirements of the manual ability classification system and age were referred by the therapists to the study. Control subjects were recruited by public advertisement. All subjects were paid for their travel expenses and participation. Experiments were conducted in the Computational Motor Control Laboratory of Ben-Gurion University of the Negev.

B. Experimental Apparatus and Experimental Procedure

An augmented environment was used to create a grip and lift task. The system [Fig. 1(a)] provides both visual and haptic feedback, giving the impression of interaction with a real object. For each subject, the index finger and thumb of the dominant hand were each connected to a robotic arm (PHANTOM Desktop by SensAble) via firmly fixed thimbles [Fig. 1(b)]. The system measures the position of each finger, calculates the acceleration of the object, updates the position of the object, and computes the resultant forces on the fingers. These forces are applied to the fingers by torque motors to create the appropriate feedback. The visual feedback combined with the force feedback creates the impression of interaction with a real object.

Participants were instructed to set on an adjustable chair in front of a table. If required, we helped subjects with adjustments in sitting; the chair was adjusted so that the participant's forearm was approximately parallel to its surface when robotics arm were used to grasp the virtual objects. Each subject was requested to keep his/her shoulder adducted to the trunk with the vertical upper arm, elbow in 90° flexion, forearm in mid-position between pronation and supination, wrist in neutral position, hand opening and resting on the table [Fig. 2(a)].

The experimental procedure was identical to that reported in Mawase and Karniel for neurologically intact individuals [20]. Each subject was asked to grasp and, with his/her dominant hand, lift a virtual object up to a target point, 21 cm above a table. The Reachin Display with the Sensegraphics software performs virtual integration of the haptic device with stereo graphics for an augmented reality experience. A purple box ($9 \times 12 \times 12$ cm) represented the object, and a small yellow circle (1.5 cm radius) indicated the location of the target toward which subjects were instructed to move the object [Fig. 2(a)].

Each subject performed 99 lifting trials, with the weights of the objects—ranging between 100 and 400 g—being selected randomly in each trial, A series of four trials with increasing weights (100, 200, 300, 400 g), followed by a catch trial (250 g), appeared randomly eight times during the experiment, with no overlapping [Fig. 2(b)]. It is important to note that the shape of the object did not change during the trials.

To probe the perceptual deficit in the weight discrimination, we asked each subject the following questions in the order given below after they had performed all the trials of the experiment.

1) Did you observe any changes in the object's weight?
2) Did you observe a random change in the object's weight?

3) Did you observe any similarity between the trials?
4) Did you observe a sequence of changes in the object's weight?

C. Data Analysis

Force and position data were sampled at 100 Hz using virtual reality software (SensAble Technologies, Woburn, MA). This sampling rate is sufficiently high for analyzing the subjects' movements, and it is sufficiently low to facilitate the virtual object rendering. This was also the sampling rate in our previous study [20]. Custom software written in Matlab (MathWorks, Natick, MA) was used for all subsequent analysis. Forces were generated and recorded at the end point of each phantom and then Grip force was calculated as an average of the forces produced by the index finger and the thumb along the horizontal axis crossing the virtual object, in the direction of the squeeze that prevented the object from slipping. The vertical position of the object in each trial was analyzed to detect the onset time (t_0) of the movement by using an algorithm based on a minimum acceleration criterion with constraints (MACC) [44]. The MACC hypothesis asserts that the observed movement is a result of minimizing the integrated squared acceleration under the constraints at the beginning and end of movement, the velocity and acceleration are zero and limit on the maximum jerk. The jerk is formulated as the control signal, since it correlates with the neural activation signal, which in most models is smoothed to generate the force in the muscle and hence the acceleration [35].

Here, we assumed that the first part of the vertical movement can be approximated by the following trajectory:

$$x(t) = \begin{cases} x_0, & t \le t_0 \\ x_0 + \dfrac{1}{6}U_m(t-t_0)^3, & t_0 \le t \le t_1 = t_0 + \Delta T \end{cases}. \tag{1}$$

Where U_m is the actual maximum jerk during this segment, and x_0 is the initial static position. We used the MACC-based algorithm to fit U_m and t_0 to each trial and set $\Delta T = 70$ ms. In this study, we were particularly interested in the first part of the lifting movement, since in this phase of movement there are no feedback mechanisms, at least in neurologically intact subjects.

Temporal coordination was evaluated in terms of the time interval between the onset of the grip force [point at which contact is made with the object and the grip force begins to increase (>0 N)] and the onset of movement (t_0) (Fig. 3).

We measured the vertical trajectory of the object and sought to extract the motor command based on the following spring-mass model, previously developed to describe human wrist movements [45], [46]

$$M_i \cdot \ddot{x}_i + B \cdot (\dot{x}_i)^{\frac{1}{5}} + K \cdot \left(x_i - x_{\mathrm{eq}_i}\right) = 0. \tag{2}$$

Where x_i is the position of an object of mass M_i in trial i, B is the damping coefficient, K is the spring stiffness and x_{eq_i} is the resting, or the motor command in trial i. This nonlinear model is derived from a combination of nonlinear muscle properties and a spinal reflex mechanism, the latter being driven mainly by feedback from muscle spindle receptors [47]. The control signal in our model sets the equilibrium value x_{eq_i}, which represents a central motor command setting the threshold of the stretch reflex [48], [49]. Pulse step control is effective in producing rapid and well controlled positioning of the mass in this system. Since pulse step control is effective in producing smooth and well controlled positioning of the mass in this system, and since the first phase of the movement is of particular interest to us, we assumed that the motor command to be constant in this part of movement. Optimization problem was solved to find the best motor command (x_{eq_i}) from all feasible solutions to minimize the root mean square error between the average jerk of the actual data and the average jerk of the model prediction that based on MACC algorithm described above. The free parameters of the model were matched for the first 70 ms (Fig. 4) of each trial (x_{eq_i}) and for each subject (B, K) by using a simple optimization algorithm (Optimization Toolbox, MathWorks, Natick, MA). Altogether, we have extracted for

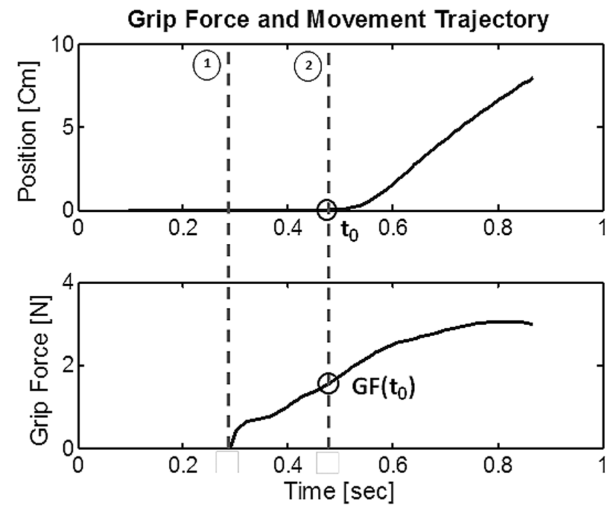


Fig. 3. Position of the virtual object (single trajectory movement) and grip force trajectories from a representative control subject. Timing of grip force coordination (execution) was measured for specific lift events: ① point at which contact is made with the object and the grip force begins to increase (>0 N); ② movement onset t_0.

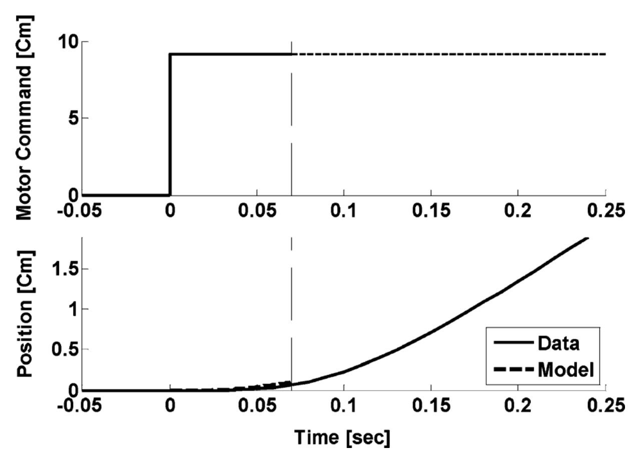


Fig. 4. Extracting the motor command; The motor command as a step control function at the initial phase of the movement. Top: Step command. Bottom: Position as a function of time obtained from a representative subject (solid line) and the model fitting for the first 70 ms (dashed line).

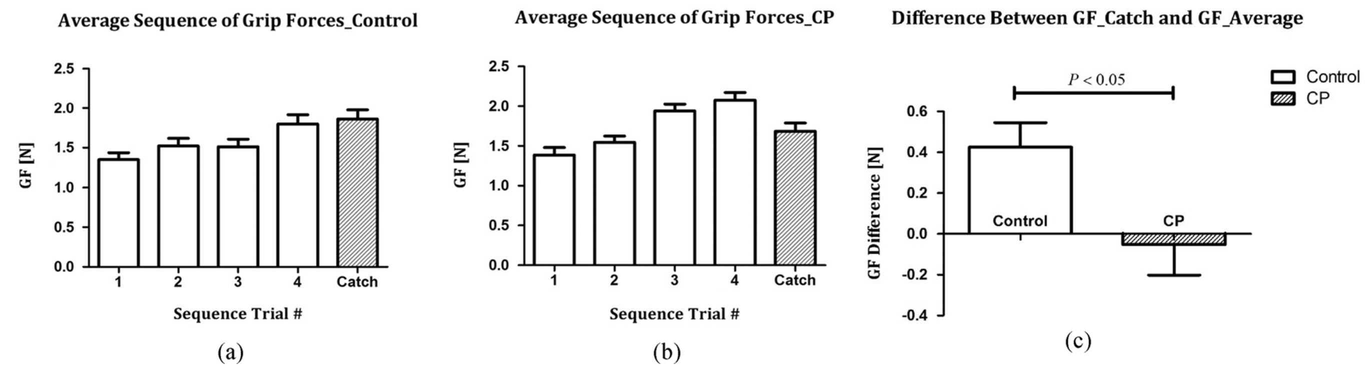


Fig. 5. Grip forces in the series trials in the initial part of the movements in control and dCP subjects. (a) Average sequence of forces across the entire series of increasing weights in control subjects; white bars represent the average grip force while lifting a series of increasing weights of 100, 200, 300, 400 g, and black bar represents the average grip force in the catch trial (250 g). (b) Average sequence of forces across the entire series of increasing weights in CP subjects. (c) Difference between the average grip force at the catch trial and the average grip force for the series of four trials with increasing weights in control subjects and individuals with CP. Values are means ± SEM.

each trial, the best fit of the motor command accounting for the first 70 ms of the movement. The level of statistical significance for all measures was set at $P < 0.05$.

We also sought correlation (Pearson's correlation) between each one of the seven tasks of the JTT hand function test and the predictive control variables (grip force at the movement onset, and the motor command) as well as the execution variable (time interval between onset of grip and the onset of the movement).

III. Results

A. Lack of Predictive Control in CP

Fig. 5(a) shows the average sequence of forces across the entire series of increasing weights in control subjects. From this Figure, it is evident that the highest grip force that the control subjects applied was that in the catch trials; this finding indicates that the subjects expected a higher weight than was actually available (recall that in the catch trial, the weight was "unexpectedly" lowered to 250 g; see Fig. 3). In contrast, subjects with CP [Fig. 5(b)] did not expect higher weight in the catch trials. For these subjects, the grip force at the movement onset increased as the weight increased and decreased as the weight decreased, i.e., subjects with CP applied the proper grip force under each load condition.

To quantify the predictive control for both control and CP subjects, we calculated the difference between the average grip force in the catch trial and the average grip force for the series of four trials with increasing weights [Fig. 5(c)]. Control subjects showed significant positive difference ($\mathrm{P} < 0.05$), suggesting that subjects predicted the subsequent weight rather than the average weight. However, for CP subjects the difference was not significant ($\mathrm{P} = 0.7451$), which indicated that predictive control is impaired in subjects with spastic dCP. Based on the subject's answers to the first two questions, most subjects (all five control subjects and four out of five cerebral palsy subjects) were clearly able to discriminate between objects of different weights. The results therefore indicate that the perceptual ability of the diplegic subjects was unimpaired, and reinforce the hypothesis that dCP subjects have higher-order impairment in sensory-motor integration.

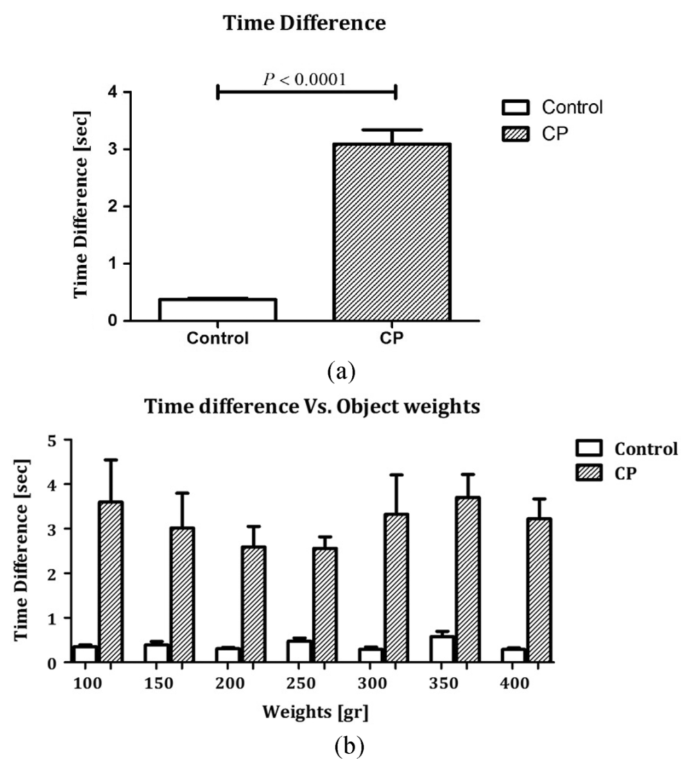


Fig. 6. Time interval between the onset of the grip force and the onset of the movement. (a) In control and dCP subjects. (b) Time interval between control and dCP subjects for each object weight. Values are means ± SEM.

B. Prolonged Grasp in CP

In the CP subjects, the time interval between the onset of grip and the onset of movement was significantly longer than that for the control subjects ($\mathrm{P} < 0.0001$) [Fig. 6(a)]; this finding implies that CP subjects need time to obtain sensory information about an object's weight. Fig. 6(b) shows the time difference measurement (mean ± SEM) between dCP and control subjects and between objects weights (100, 150, 200, 250, 300, 350, 400 g). The difference between groups is statistically significant ($\mathrm{P} < 0.05$) for each and every weight. However, no significant difference in the time difference measurement was observed between weights in each group. This finding supports

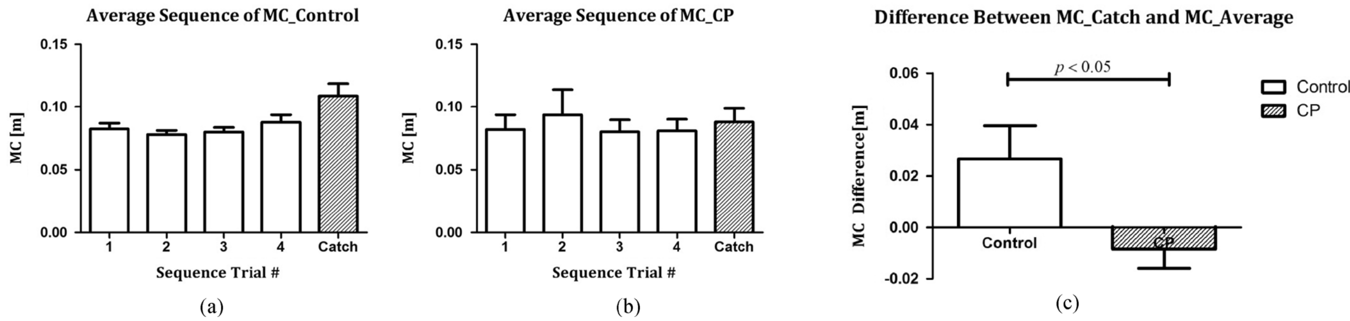


Fig. 7. Motor commands (MC) in the series trials in the initial part of the movements in control and dCP subjects. (a) Average sequence of motor commands across the entire series of increasing weights in control subjects; white bars represent the average of the motor commands while lifting a series of increasing weights of 100, 200, 300, 400 g, and black bar represents the average of the motor commands in the catch trial (250 g). (b) Average sequence of motor commands across the entire series of increasing weights in CP subjects. (c) Difference between the average motor command in the catch trial and the average motor command for the series of four trials with increasing weights in control subjects and individuals with CP. Values are means ± SEM.

TABLE II
CORRELATION OF PREDICTIVE AND EXECUTION CONTROL VARIABLES WITH FUNCTIONAL TEST RESULTS

variable		*JTT*						
		writing	turning pages	picking up small objects	feeding	stacking checkers	picking up large light objects	picking up large heavy objects
Predictive	GF	0.45 (0.51)	-0.16 (0.84)	-0.24 (0.76)	-0.37 (0.63)	-0.01 (0.99)	-0.20 (0.80)	0.10 (0.90)
	MC	**-0.99 (0.01)**	-0.46 (0.54)	-0.31 (0.70)	-0.62 (0.38)	-0.45 (0.55)	-0.37 (0.62)	-0.28 (0.72)
Execution	TI	0.04 (0.96)	0.93 (0.07)	**0.97 (0.03)**	0.43 (0.57)	**0.96 (0.04)**	**0.96 (0.04)**	**0.97 (0.03)**

JTT = Jebsen-Taylor hand function test; **GF** = grip force at the movement onset; **TI** = time interval between the onset of grip and the onset of movement; **MC** = motor command. Values represent Pearson's correlation coefficient (r) with the corresponding significance (P-value) in parentheses.
Based on data from 5 dCP subjects .

the hypothesis that dCP use feedback strategy, instead of planning ahead and therefore need more time to obtain sensory information about an object's weight to adjust their movement.

C. Extracting the Motor Command

Fig. 7(a) shows the average sequence of motor commands across the entire series of increasing weights in control subjects. The highest motor command was evident in the catch trial, indicating that the control subject's brain planned for heavier weights after the fourth (and last) weight in the series. In contrast, in persons with CP the motor command process was impaired [Fig. 7(b)]: there was no difference between the motor commands for the series of trials.

We also calculated the difference between the average motor command in the catch trial and the average motor command for the series of four trials with increasing weights [Fig. 7(c)]. Control subjects showed a significant positive difference ($P < 0.05$), suggesting that the motor command is under predictive control and that subjects plan for the subsequent weight rather than the average weight. However, for CP subjects, the difference was not significant ($\mathrm{P} = 0.3329$), which indicates that the motor command, too, is impaired in persons with spastic dCP.

D. Correlation Between Predictive Control Variables and Functional Measures

Table II presents the correlation of predictive control variables (grip force at the movement onset, and the motor command) as well as the execution variable (time interval between onset of grip and the onset of the movement) with the outcomes of the JTT hand function test in persons with spastic dCP. Measures of precision grasp planning (grip force at the movement onset and motor command) did not correlate with any of the hand function tests for the dominant hand. However, for the dominant hand there was a significant correlation between measures of precision grasp execution (time interval between the onset of grip and the onset of movement) and four of the seven tasks of the JTT hand function test.

IV. DISCUSSION

In this study, five subjects with spastic dCP demonstrated the use of feedback control rather than predictive control in lifting a series of objects with increasing weights. They presented a significantly longer time interval between the onset of grip and onset of movement than control subjects, and did not predict the next object in the lifting task, which demonstrated that the impairments in predictive control and in performing the task presumably result from an inability to form or access internal models of object properties due to a higher-order impairment in sensory-motor integration. This disability correlated with motor measures that were obtained from the JTT hand function test.

Previous studies, in particular by Gordon and Duff [37]–[39] focused on the performance of hand function and predictive control in children with hemiplegic cerebral palsy. Here we tested persons with spastic diplegic cerebral palsy, a group which was typically studied for lower extremity deficits. Our results are consistent with the previous results, both groups of disorder (diplegic and hemiplegic) exhibit problems with anticipatory control that are based on disturbed sensory information due to a poor internal representation of the object.

We have measured two type of variables, predictive variables (the grip force at the movement onset and the motor command) and execution variable (the time between the onset of the grip force and the onset of the movement), the latter indicates the time needed to develop appropriate lifting forces, while the former indicate the expected weight of the object before sensory feedback of the object's weight is available at lift-off.

A. Grip Force

To examine whether predictive feedforward control is used to predict a succeeding weight in a series of increasing weights, we measured the grip force at the movement onset for each trial in the series and for each catch trial. Neurologically intact subjects, including those in our study, are able to predict the next object in lifting a series of virtual objects through internal models of object weight [20], [32], [50], [51]. However, our dCP study population did not predict the weight of the next object in the lifting task and used sensory feedback control to execute the task. Our findings are similar to those described previously for stroke patients and children with hemiplegic CP [10], [37], [38]. A possible explanation for the lack of predictive control in persons with dCP is associated to the incomplete internal representations of the objects, as suggested by the strong relationship between two-point discrimination and anticipatory control reported previously [37]. Our results indicate that the diplegic subjects did not use information from previous trials to plan the grip force for the next trial, due to their inability to formulate motor plans based on internal representations. We have tested persons with dCP, and they did not show any deficits in estimating the weights of the objects. Therefore, we believe that the observed execution deficit is due to higher-order dysfunction in motor adaptation capability rather than effectors dependent deficit.

B. Motor Command

Based on previous studies [34], [35], we assumed that the jerk during the first part of the movement represents the results of a predictive feedforward motor command, namely, a command sent to the muscles in accordance with the predicted environment. Therefore, if the environment unexpectedly changes and the motor command is generated in a predictive feedforward fashion during the first part of the movement, the jerk must change according to the change in the environment. This expectation was fulfilled in the control subjects but was clearly not the case in the dCP subjects, who demonstrated a lack of predictive feedforward control in our experimental set-up.

Our results were obtained with a unique data analysis technique—inspired by the MACC hypothesis [35], [44]—that targets the very beginning of the movement by extracting the motor command in the first 70 ms of the movement. We believe that the motor command in the very first part of the movement reflects clearly and accurately the motor planning or lack thereof and is less susceptible to influence of feedback.

C. Prolonged Execution

The execution of grasp variable—measured by the time interval between the onset of grip force and the onset of movement—was longer in the subjects with spastic dCP than in the control subjects. This finding is similar to those described previously in children with hemiplegic CP [52], [53], in patients with chronic pure motor hemiparesis [54] and in patients with stroke [10]. In such patients, the damage could be due to sustained deficits in the motor neurons pathways that connect that motor cortex and the spinal cord.

The extended duration between the onset of grip force and the onset of movement facilitate the use of feedback control instead of predictive control; however it is important to note that predictive control was observed also in slow unimpaired individuals who had similar duration as the fast individual with dCP, whereas the latter still demonstrated clear lack of predictive control.

Improvement in hand function might occurs over a longer time frame than commonly would be expected as observed previously in children with CP [7]. More evidences suggest that therapies that focus on intensive practice are promising [55], [56]. Such intensive treatments can also be reflected by changes in cortical activation patterns after the therapy. The improvements in hand function during development provide another theoretical basis for providing intensive practice, suggesting functional and structural plasticity in the human brain. However, further long term studies are needed to examine the efficiency of the rehabilitation.

D. Correlation of Functional Measures With Predictive Control

In the subjects with dCP, variables of planning precision grasp (grip force at the movement onset and motor command) did not correlate with any of the hand function tasks (JTT), with the exception of a high negative correlation between the writing task and the motor command. However, the time interval between the onset of grip and the onset of movement correlated strongly with most tasks of the JTT. Our results are consistent with previous studies in stroke patients [10] and children with hemiplegic CP [37].

The significant correlation between the execution of grasp (time interval) and four tasks of the hand function test (JTT) suggests that conventional clinical measures used in the assessment of patients with diplegic cerebral palsy are primarily measures of execution. The correlation between JTT scores and the time interval is based only on four subjects, however, it is still of interest since we found significant correlations that are consistent with previous findings [10], [39]. These results may be critical to understanding relationships between motor impairment and functional motor behavior.

Despite the fact that our dCP subjects classified at MACS level II presented high values of the time interval between onset of grip force and onset of movement, they showed impaired predictive control similar to that observed for level I individuals. These results validate the hypothesis that persons with CP have impaired predictive control, with the impairment being independent of manual ability deficit levels. However, further studies are required to draw definitive conclusions and to examine the relationships between clinical measurements and motor performances.

E. Feedforward or Feedback Control?

Our conclusion that dCP have impaired predictive control is in concert with a number of recent studies using different tasks and movement analyses that indicated predictive control deficits in persons with CP: Mutsaarts *et al.* [57], [58] explored anticipatory planning in children with hemiparetic CP by measuring the initial reaction time as representative of anticipatory planning. Their results indicate a lack of motor planning and support feedback control (in their terminology: step-by-step correction). Gordon and Duff [37], [38] found that children with hemiplegic CP exhibited both prolonged delays between movement phases and sequential (rather than parallel) generation of grip and load forces. They typically initially increased grip force in conjunction with negative load force (pushing the object down); this may indicate a problem in anticipation that is compatible with our findings. Mutsaarts *et al.* [58] posited that the selection of grip is critically dependent on the action that is to be performed with the object. Therefore, they claimed that proper grip planning requires an ability to consider the forthcoming perceptual motor demands associated with the goal of the action sequence. They observed that children with hemiplegic CP selected a grip that was predominantly affected by the grip used in a previous trial and was not flexibly adapted to changes in the task context. Moreover, their grip was the one most comfortable at the beginning of the movement, while control children selected a grip that led to a comfortable hand posture at the end of the grasping sequence. Those findings led to the hypothesis that individuals with CP use information that is directly available rather than anticipating the forthcoming demands [58]. All the above studies suggest a central origin for the observed deficits in persons with CP. However, such persons also suffer from spasticity in addition to secondary peripheral deficits, and future studies should differentiate between these two sources of behavioral deficits.

F. Clinical Implications

In this study, we demonstrated that five individuals with dCP lacked predictive control in lifting a series of objects with increasing weights. We did not further investigate their abilities to adapt and learn following interventions that may use similar protocols to those used in this study, consisting of practice with catch trial interference. Other investigators have, however shown that interventions of external force field on adaptation by using catch trials will be benefit for teaching motor skills and for neuro-rehabilitation of brain-injured patients [6], [54].

The information gained from studying predictive control has clinical implications. First, evaluation of predictive control can aid the medical team in assessing the motor learning capabilities of person with dCP. Predictive control following motor adaptation and motor learning require trial-and-error practice, and motor adaptation may be an initial component in the process of motor learning [59]. Thus, studying motor predictive control allows us to begin to assess whether and to what extent the capacity for motor learning may be intact in persons with dCP. Clinicians can use the testing protocols applied in this study (with or without catch trials) as part of their interventions in aspects of a short term adaptation and motor learning. Such an intervention has indeed been suggested by Patton *et al.* [9] for stroke patients. The use of robotic training to enhance predictive feedforward control and its implications in the rehabilitation of persons with CP remains to be further investigated.

G. Conclusion

Our findings have a number of implications for persons with diplegic cerebral palsy. Although diplegic cerebral palsy form was defined as the lower extremities are severely involved and the arms are mildly involved, we observed that dCP demonstrate also deficits in hand motor predictive control in the way they failed to predict succeeding weight in a series of increasing weights. Diplegic cerebral palsy persons seem to use feedback control and information that is directly available rather than using anticipatory feed-forward control when their hands act in everyday manual activities. Further and larger studies are needed for investigating the deficits in planning and execution of hand movements of persons with diplegic cerebral palsy.

ACKNOWLEDGMENT

The authors would like to thank D. Kedar and K. Simhony for performing the hand function test. The authors also thank N. Harries and Dr. L. Copeliovitch for their help in obtaining permission for this study from the local Helsinki Committee.

REFERENCES

[1] M. Bax *et al.*, "Proposed definition and classification of cerebral palsy, April 2005," *Developmental Med. Child Neurol.*, vol. 47, pp. 571–576, 2005.

[2] P. Rosenbaum, "Cerebral palsy: What parents and doctors want to know," *Br. Med. J.*, vol. 326, pp. 970–974, May 3, 2003, 2003.

[3] A. N. Berker and M. S. Y. In, "Cerebral palsy: Orthopedic aspects and rehabilitation," *Pediatric Clin. N. Am.*, vol. 55, pp. 1209–1225, 2008.

[4] J. R. Wingert *et al.*, "Tactile sensory abilities in cerebral palsy: Deficits in roughness and object discrimination," *Developmental Med. Child Neurol.*, vol. 50, pp. 832–838, 2008.

[5] C. L. Balf and T. T. S. Ingram, "Problems in the classification of cerebral palsy in childhood," *Br. Med. J.*, vol. 2, no. 4932, pp. 163–166, 1955.

[6] T. T. S. Ingram, "A study of cerebral palsy in the childhood population of Edinburgh," *Arch. Disease Childhood*, vol. 30, pp. 85–98, Apr. 1, 1955, 1955.

[7] A.-C. Eliasson *et al.*, "Development of hand function and precision grip control in individuals with cerebral palsy: A 13-year follow-up study," *Pediatrics*, vol. 118, pp. e1226–1236, Oct. 1, 2006, 2006.

[8] A. Karniel, "Computational motor control," in *Encyclopedic of Neuroscience*, M. D. Binder, N. Hirokawa, and U. Windhorst, Eds. Berlin, Germany: Springer-Verlag, 2009, pp. 832–837.

[9] J. Patton *et al.*, "Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors," *Exp. Brain Res.*, vol. 168, pp. 368–383, 2006.

[10] P. Raghavan *et al.*, "Impaired anticipatory control of fingertip forces in patients with a pure motor or sensorimotor lacunar syndrome," *Brain*, vol. 129, pp. 1415–1425.

[11] B. Rohrer *et al.*, "Movement smoothness changes during stroke recovery," *J. Neurosci.*, vol. 22, pp. 8297–8304, Sep. 15, 2002, 2002.

[12] A. Roby-Brami *et al.*, "Reaching and grasping strategies in hemiparetic patients," *Motor Control*, vol. 1, pp. 72–91, 1997.

[13] T. Twitchell, "The restoration of motor function following hemiplegia in man," *Brain*, pp. 443–480, 1959.

[14] A. M. Wing *et al.*, "Recovery of elbow function in voluntary positioning of the hand following hemiplegia due to stroke," *J. Neurol., Neurosurg. Psychiatry*, vol. 53, pp. 126–134, Feb. 1, 1990, 1990.

[15] C. D. Marsden *et al.*, "Servo action in human voluntary movement," *Nature*, vol. 238, pp. 140–143, 1972.

[16] A. Karniel and G. F. Inbar, "Human motor control: Learning to control a time-varying, nonlinear, many-to-one system," *IEEE Trans. Syst., Man, Cybern., Part C: Appl. Rev.*, vol. 30, pp. 1–11, 2000.

[17] M. Kawato, "Internal models for motor control and trajectory planning," *Current Opin. Neurobiol.*, vol. 9, pp. 718–727, 1999.

[18] D. M. Wolpert *et al.*, "Perspectives and problems in motor learning," *Trends Cognitive Sci.*, vol. 5, pp. 487–494, 2001.

[19] D. M. Wolpert and M. Kawato, "Multiple paired forward and inverse models for motor control," *Neural Networks*, vol. 11, pp. 1317–1329, 1998.

[20] F. Mawase and A. Karniel, "Evidence for predictive control in lifting series of virtual objects," *Exp. Brain Res.*, vol. 203, pp. 447–452, 2010.

[21] R. Shadmehr and F. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *J. Neurosci.*, vol. 14, pp. 3208–3224, May 1, 1994, 1994.

[22] A. Karniel and F. A. Mussa-Ivaldi, "Sequence, time, or state representation: How does the motor control system adapt to variable environments?," *Biol. Cybern.*, vol. 89, pp. 10–21, 2003.

[23] P. R. Davidson and D. M. Wolpert, "Motor learning and prediction in a variable environment," *Current Opin. Neurobiol.*, vol. 13, pp. 232–237, 2003.

[24] R. Scheidt *et al.*, "Learning to move amid uncertainty," *J. Neurophysiol.*, vol. 86, pp. 971–985, 2001.

[25] C. Takahashi *et al.*, "Impedance control and internal model formation when reaching in a randomly varying dynamical environment," *J. Neurophysiol.*, vol. 86, pp. 1047–1051, 2001.

[26] A. G. Witney *et al.*, "The influence of previous experience on predictive motor control," *Neuroreport*, vol. 12, pp. 649–653, 2001.

[27] R. Johansson, "Sensory control of dextrous manipulation in humans," *Hand Brain*, pp. 381–414, 1996.

[28] R. M. Bracewell *et al.*, "Predictive and reactive co-ordination of grip and load forces in bimanual lifting in man," *Eur. J. Neurosci.*, vol. 18, pp. 2396–2402, 2003.

[29] P. Davidson and D. Wolpert, "Internal models underlying grasp can be additively combined," *Exp. Brain Res.*, vol. 155, pp. 334–340, 2004.

[30] J. R. Flanagan and A. M. Wing, "The role of internal models in motion planning and control: Evidence from grip force adjustments during movements of hand-held loads," *J. Neurosci.*, vol. 17, pp. 1519–1528, Feb. 15, 1997, 1997.

[31] J. R. Flanagan and S. Lolley, "The inertial anisotropy of the arm is accurately predicted during movement planning," *J. Neurosci.*, vol. 21, pp. 1361–1369, Feb. 15, 2001, 2001.

[32] R. S. Johansson and G. Westling, "Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip," *Exp. Brain Res.*, vol. 71, pp. 59–71, 1988.

[33] R. S. Johansson and K. J. Cole, "Sensory-motor coordination during grasping and manipulative actions," *Current Opin. Neurobiol.*, vol. 2, pp. 815–823, 1992.

[34] J. R. Flanagan *et al.*, "Prediction precedes control in motor learning," *Current Biol.*, vol. 13, pp. 146–150, 2003.

[35] S. Ben-Itzhak and A. Karniel, "Minimum acceleration criterion with constraints implies bang-bang control as an underlying principle for optimal trajectories of arm reaching movements," *Neural Computat.*, vol. 20, pp. 779–812, 2008.

[36] A.-C. Eliasson *et al.*, "Impaired anticipatory control of isometric forces during grasping by children with cerebral palsy," *Developmental Med. Child Neurol.*, vol. 34, pp. 216–225, 1992.

[37] A. M. Gordon and S. V. Duff, "Relation between clinical measures and fine manipulative control in children with hemiplegic cerebral palsy," *Developmental Med. Child Neurol.*, vol. 41, pp. 586–591, 1999.

[38] A. M. Gordon and S. V. Duff, "Fingertip forces during object manipulation in children with hemiplegic cerebral palsy. I: Anticipatory scaling," *Developmental Med. Child Neurol.*, vol. 41, pp. 166–175, 1999.

[39] A. M. Gordon *et al.*, "Fingertip forces during object manipulation in children with hemiplegic cerebral palsy. II: Bilateral coordination," *Developmental Med. Child Neurol.*, vol. 41, pp. 176–185, 1999.

[40] A. Ferrari *et al.*, "Functional reaching discloses perceptive impairment in diplegic children with cerebral palsy," *Gait Posture*, vol. 32, pp. 253–258, 2010.

[41] A. Berthoz, *The Brain's Sense of Movement: Perspectives in Cognitive Neuro-Science*. Cambridge, MA: Harvard Univ. Press, 2002.

[42] L. S. Bundy, A. C. , A. G. Fisher, and E. A. Murray, *Sensory integration: Theory and practice*. Philadelphia, PA: F.A. Davis, 2002.

[43] R. H. Jebsen *et al.*, "An objective and standardized test of hand function," *Arch. Phys. Med. Rehabil.*, vol. 50, pp. 311–319, 1969.

[44] L. Botzer and A. Karniel, "A simple and accurate onset detection method for a measured bell-shaped speed profile," *Front Neurosci.*, vol. 3, no. 61, 2009.

[45] C. C. A. M. Gielen and J. C. Houk, "Nonlinear viscosity of human wrist," *J. Neurophysiol.*, vol. 52, pp. 553–569, 1984.

[46] C. H. Wu *et al.*, "Nonlinear damping of limb motion," *Biomechan. Movement Organizat.*, pp. 214–235, 1990.

[47] C. C. A. M. Gielen and J. C. Houk, "A model of the motor servo: Incorporating nonlinear spindle receptor and muscle mechanical properties," *Biol. Cybern.*, vol. 57, pp. 217–231, 1987.

[48] A. Feldman, "Functional tuning of the nervous system with control of movement or maintenance of a steady posture-II controllable parameters of the muscle," *Biophysics*, vol. 11, pp. 565–578, 1966.

[49] J. C. Houk and W. Z. Rymer, "Neural control of muscle length and tension," *Motor Control*, pp. 247–323, 1981.

[50] M. G. Andrew *et al.*, "Memory representations underlying motor commands used during manipulation of common and novel objects," *J. Neurophysiol.*, vol. 69, no. 6, pp. 1789–1796, 1993.

[51] R. S. Johansson and G. Westling, "Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip," *Exp. Brain Res.*, vol. 66, pp. 141–154, 1987.

[52] J. Duque *et al.*, "Correlation between impaired dexterity and corticospinal tract dysgenesis in congenital hemiplegia," *Brain*, vol. 126, pp. 732–747, Mar. 1, 2003, 2003.

[53] H. Forssberg *et al.*, "Impaired grip-lift synergy in children with unilateral brain lesions," *Brain*, vol. 122, pp. 1157–1168, Jun. 1999, 1999.

[54] R. Wenzelburger *et al.*, "Hand coordination following capsular stroke," *Brain*, vol. 128, pp. 64–74, Jan. 1, 2005, 2005.

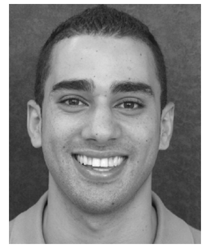
[55] A. M. Gordon *et al.*, "Methods of constraint-induced movement therapy for children with hemiplegic cerebral palsy: Development of a child-friendly intervention for improving upper-extremity function," *Arch. Phys. Med. Rehabil.*, vol. 86, pp. 837–844, 2005.

[56] A. M. Gordon *et al.*, "Efficacy of constraint-induced movement therapy on involved upper-extremity use in children with hemiplegic cerebral palsy is not age-dependent," *Pediatrics*, vol. 117, p. e363, 2006.

[57] M. J. H. Mutsaarts *et al.*, "Anticipatory planning of movement sequences in hemiparetic cerebral palsy," *Motor Control*, vol. 9, pp. 439–458, 2005.

[58] M. Mutsaarts *et al.*, "Anticipatory planning deficits and task context effects in hemiparetic cerebral palsy," *Exp. Brain Res.*, vol. 172, pp. 151–162, 2006.

[59] A. J. Bastian, "Understanding sensorimotor adaptation and learning for rehabilitation," *Current Opin. Neurol.*, vol. 21, pp. 628–633, 2008.



Firas Mawase was born in Israel, in 1986. He received the B.Sc. and M.Sc. (direct track) degrees from the Department of Biomedical Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel, in 2009 and 2010, respectively. He is currently working toward the Ph.D. (combined track) degree in biomedical engineering.

His research interests include motor control, human motor learning, motor memory and motor rehabilitation.

Mr. Mawase received the FARAN Foundation scholarship for graduate students. He is a member of the Society for the Neural Control of Movement and the Society for Neuroscience.

Simona Bar-Haim was born in Romania, in 1955. She received the B.PT. in physiotherapy and the M.Sc. degree in physiology from Tel-Aviv University, Tel-Aviv, Israel, and the Ph.D. degree in neurophysiology at the Faculty of Health Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel, in 1988, 1996, and 2005, respectively.

She is recognized as an expert on Cerebral Palsy gait analysis and motor learning. She directs the Human Motion Analysis Laboratory at Assaf-Harofeh Medical Center and is with the Department of Physiotherapy, Faculty of Health Sciences at Ben-Gurion University. She led several international and Middle East research projects to evaluate interventions that improve walking in "natural environments" in children and teenagers with CP. She initiated and is the scientific director of an EU consortium that developed and validates a system that induces chaotic perturbation to prevent falling in elderly fallers. Her studies are supported by the EU in the frame of FP7, Cerebral Palsy International Research Foundation and USAID-MERC.

Amir Karniel (SM'06) was born in Jerusalem, Israel, in 1967. He received the B.Sc., M.Sc., and Ph.D. degrees, in 1993, 1996, and 2000, respectively, all in electrical engineering from the Technion-Israel Institute of Technology, Haifa, Israel.

He served four years in the Israeli Navy as an electronics technician and worked during his undergraduate studies at Intel Corporation, Haifa, Israel. For two years he had been a postdoctoral fellow at the Department of Physiology, Northwestern University Medical School and the Robotics Lab of the Rehabilitation Institute of Chicago. Since 2003, he is with the Department of Biomedical Engineering at Ben-Gurion University of the Negev, where he serves as the Head of the Computational Motor Control Laboratory and the organizer of the annual International Computational Motor Control Workshop. In the last few years his studies are funded by awards from the Israel Science Foundation, The Binational United-States Israel Science Foundation, the National Institute of Psychobiology in Israel, and the US-AID Middle East Research Collaboration. His research interests include human machine interfaces, haptics, brain theory, motor control, and motor learning. He is on the Editorial Board of *Frontiers in Neuroscience*.

Dr. Karniel received the E. I. Jury award for excellent students in the area of systems theory, and the Wolf Scholarship award for excellent research students. He is on the Editorial Board of the IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART A and a Guest Editor for a special issue of the IEEE TRANSACTIONS ON HAPTICS.