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RESEARCH NOTE

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Grip-load force coordination in cerebellar patients

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Abstract The study examined the anticipatory grip force modulations to load force changes during a drawer-opening task. An impact force was induced by a mechanical stop which abruptly arrested movement of the pulling hand. In performing this task, normal subjects generated a typical grip force profile characterized by an initial force impulse related to drawer movement onset, followed by a ramp-like grip force increase prior to the impending load perturbation. Finally, a reactive response was triggered by the impact. In patients with bilateral cerebellar dysfunction, the drawer-opening task was performed with an alternative control strategy. During pulling, grip force was increased to a high (overestimated) default level. The latter suggests that cerebellar patients were unable to adjust and to scale precisely the grip force according to the load force. In addition, the latency between impact and reactive activity was prolonged in the patients, suggesting an impaired cerebellar transmission of the long-latency responses. In conclusion, these data demonstrate the involvement of cerebellar circuits in both proactive and reactive mechanisms in view of predictable load perturbations during manipulative behavior.

Key words Grip force · Load force · Anticipation · Cerebellum · Perturbation

Introduction

Numerous degrees of freedom are available during the execution of skilled movements. Therefore, organizational strategies and coordination rules need to be integrated by the central nervous system to reduce the demands on the control structures and the degrees of freedom that are effectively controlled (Bernstein 1967). During manipulative activities such as lifting or transporting objects, one coordination rule is the anticipatory modulation of grip force with respect to load force (Johansson and Westling 1984; Flanagan et al. 1993; Flanagan and Tresilian 1994). This basic coordination mechanism provides the means for adequate grip force regulation according to movement kinematics and characteristics of gravity and inertia. Another external force that needs to be considered during manipulation is impact forces encountered at collisions. How are such load perturbations controlled in order to avoid injury or slipping of the object? Johansson and Westling (1988) demonstrated that when subjects dropped a ball from one hand into a receptacle held with a precision grip by the other hand, grip force increased in anticipation of the collision. It thus appears that proactive control strategies are preferred when disturbances are self-induced or caused by a predictable environmental event that might destabilize the grasp. In this respect, the role of the cerebellum in anticipatory mechanisms has been suggested (Stein and Glickstein 1992).

In the paradigm used by Johansson and Westling (1988), the limb remained in a quasi-stationary position prior to impact. Therefore, the question remains whether similar control strategies are employed when the collision is determined by self-motion. The task used in the present study involved opening a drawer as far as its mechanical stop. The aims of the experiment were (1) to assess grip force modulation and its underlying rules prior to and following an impact during opening of a drawer manipulandum and (2) to investigate whether the rules observed in healthy subjects are impaired in cerebellar patients.

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Table 1 Clinical features of the patients (cerebellar symptoms: *Dd* dysdiadochokinesis, *Dy* dysmetria during finger-to-nose pointing, *Ny* nystagmus, *Po* increased postural sway, *Re* rebound effect, *PICA* posterior inferior cerebellar artery)

Age (years)	Diagnosis/neuroradiological findings	Symptoms
26	Tumor in fourth ventrical, causing compression	Dy, Dd, Po
27	Autosomal cerebellar atrophy	Dd, Ny
30	Idiopathic cerebellar atrophy of unknown origin	Dy, Dd, Ny, Re, Po
36	Bilateral PICA infarction: ischemic lesion in hemispheres	Dy, Dd, Po, Ny
67	Bilateral PICA infarction: ischemic lesion in hemispheres	Dy, Dd, Po

Materials and methods

Patients

Five patients with bilateral cerebellar dysfunction were tested (five males aged 26–67 years, mean 39±19 years). Details of the patients' deficits are listed in Table 1 together with findings of CT or MRI scans. Informed consent was obtained prior to testing and all the procedures were approved by the local ethics committee. The patients were submitted to a clinical examination before the start of the experiment which included tests of stance stability, ocular and arm movements (nystagmus, diadochokinesis, rebound effect, finger-to-nose test, finger-finger pointing, arm postural stability, postural sway with and without vision). Five age-matched control subjects were also tested (five males aged 26–68 years, mean 41±20 years).

Task and manipulandum

Subjects were prompted by a go signal to grasp the drawer handle with a precision grip between the tips of the index finger and thumb, pulling out the drawer as far as its mechanical stop, which corresponded to a distance of 7 cm. At impact, the load force increased sharply, depending on the speed of the drawer pull. Subjects performed 30 consecutive trials with vision. They were told to use their preferred hand and move at their comfort pace. Each trial was initiated by the experimenter with an auditory trigger signal.

The drawer manipulandum illustrated in Fig. 1 was mounted in a vertically oriented panel. Two pairs of strain gauges were located on the upper and lower half of the drawer's handle to measure grip force (normal to the surface), which represented the mean of the forces exerted from above by the thumb and from below by the index finger. Two other pairs of strain gauges were inserted in series with the handle to measure load force (tangential to the surface), which represented a composite force, including inertial and viscous components. Position of the drawer was measured by a resistive linear potentiometer.

Rectified and filtered EMG was recorded by flexible silver-coated PVC surface electrodes applied to the first dorsal interosseous muscle, a primary intrinsic hand muscle active during the lateral thumb-finger precision grip. Grip and load force were recorded at 400 samples/s, drawer position at 800 samples/s. Acquisition and data processing were performed by the SC/ZOOM system, developed at the Department of Physiology, Umeå University, Sweden. The statistical significance of differences in the dependent variables was assessed by means of unpaired *t*-tests. Group means ± SD of the subject means are reported.

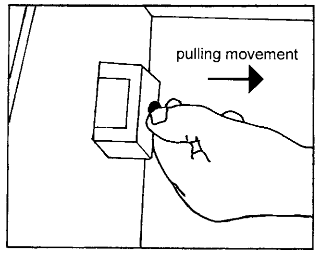


Fig. 1 Top view of the drawer-opening manipulandum. Using a lateral thumb-finger precision grip, the subject grasps the handle and opens the drawer until the mechanical stop arrests the movement

Results

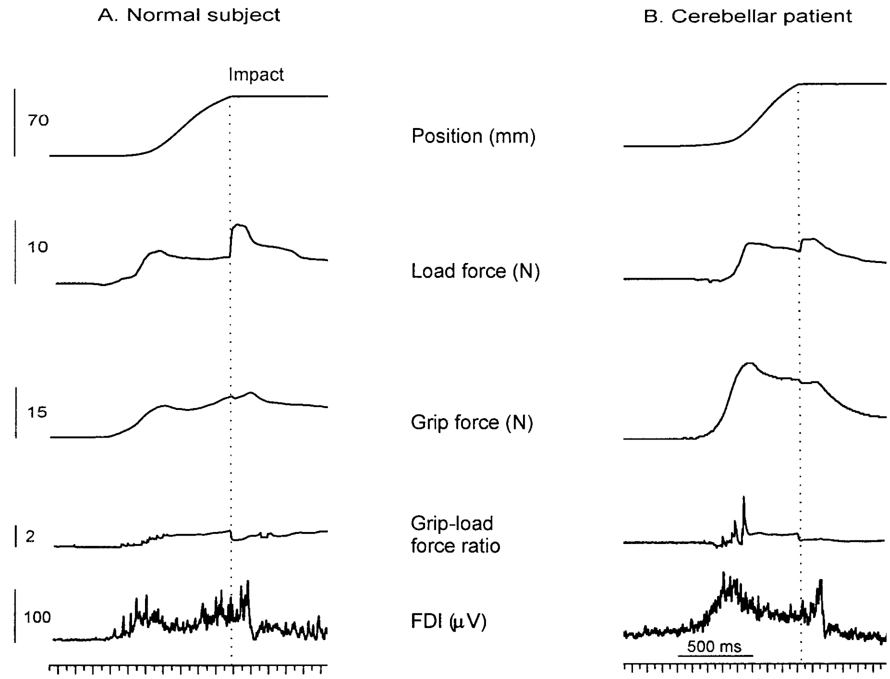
The drawer-opening task comprised two consecutive phases: a premovement phase during which loading occurs while the drawer remains in a stationary position, and a movement phase during which the drawer is opened until the mechanical stop arrests the movement. During the premovement phase, grip force is regulated in accordance with load force to set the drawer in motion. During the movement phase, grip force has to be balanced with respect to the impending load perturbation.

In view of the potential role of the cerebellum in movement planning, two issues were considered to be important in normal subjects versus cerebellar patients: (1) grip force regulation for performing the drawer-opening demands, i.e., *proactive grip force control*, and (2) the triggered response resulting from the load perturbation at the mechanical stop, i.e., *reactive grip force control*. First, proactive grip force control was evaluated by measuring the maximum grip force associated with the initial outward acceleration of the drawer (i.e., onset peak) and the magnitude of the force output at the impact. These measurements represented the amount of anticipated grip force in view of drawer movement onset and of counteracting the load perturbation at impact. Second, reactive grip force control was evaluated by determining the delay and magnitude of the grip force increase evoked by the impact. In addition, the delay of the reflex-like EMG response was computed. These measurements referred to the reactive components associated with the load perturbation.

Proactive grip force control

Fig. 2 shows representative profiles for a normal subject and a cerebellar patient. The results showed that maximum grip force at the onset peak was significantly higher for cerebellar patients (20.9±5.2 N) than for normal subjects (10.1±2.0 N), $P<0.01$. This suggests that patients greatly overestimated the grip force associated with drawer movement onset. The grip force output at the mechanical stop tended to be higher for patients

Fig. 2A, B Representative position, forces, and EMG recordings from a normal subject and a cerebellar patient (no. 4 from Table 1). Plots show averaged data from 30 trials. Note the difference in grip force strategy between the normal subject **(A)** and the cerebellar patient **(B)** when performing the drawer-opening task with a mechanical stop



(16.7±6.5 N) than for normal subjects (11.3±2.5 N), but the difference did not reach significance.

That the high level of grip force generated by the cerebellar patients reflected a disturbance in coordinating the force outputs was demonstrated by examining the grip-load force ratio. This force ratio was significantly higher for cerebellar patients (2.7±0.7) than for normal subjects (1.3±0.2) at the onset peak as well as at the impact (1.9±0.4 vs 1.2±0.1); P<0.02 for both. This observation was made despite similar load forces at the onset peak, i.e., 7.8±1.1 N vs 7.5±0.5 N, and at the impact, i.e., 8.9±1.8 N vs 9.3±1.2 N, for patients and normals, respectively.

In addition to these differences in grip-load force coordination between cerebellar patients and normal subjects, the means by which the drawer-opening task was performed differed for both groups. In normal subjects, the grip force profile consisted of two phases, which can be neatly related to the events of drawer movement onset and impending load perturbation at impact (Fig. 2, left panel). After grasping the handle, normal subjects raised their grip force in parallel with the load force to set the drawer in motion. After an initial grip force peak which was attained shortly after drawer movement onset, a modest decline occurred corresponding to a decrease or stabilization in load force. Then, about 200 ms before impact, the profiles of grip and load force deviated: whereas load force stabilized up to impact, grip force showed a ramp-like proactive increase to control the expected load force peak at the mechanical stop. In addition, the impact triggered a reflex-like response. These findings in normal subjects confirm previous results, which also showed that proactive grip force increase correlated significantly with the load force peak at impact for the majority of the subjects (Serrien et al. 1999).

The cerebellar patients demonstrated an alternative control strategy in performing the drawer-opening task (Fig. 2, right panel). In particular, they increased grip force to a high default level at the start, attaining a peak value around drawer movement onset. Thereafter, grip force was slowly reduced but remained at a relatively high level until the drawer was arrested at the mechanical stop, again triggering a reactive response. It is worth mentioning that occasional anticipatory grip force increases were observed in these patients; yet the behavior was never persistent across trials.

This between-group distinction in task performance illustrates that normals and cerebellar patients adopted different control strategies which, however, did not affect the primary aim of goal reaching, i.e., opening the drawer without loosing the handle. The exception was one patient with the most severe clinical symptoms who often lost the handle of the drawer at the moment of impact. Overall, these data confirm previous results which revealed the use of an alternative control strategy in clinically recovered unilateral cerebellar patients. In these patients, the unaffected hand showed an anticipatory grip force profile whereas the affected hand used a default level of grip force which was sustained as far as the mechanical stop (Serrien and Wiesendanger 1999).

Reactive grip force control

The load perturbation evoked a reflex-like response for which the latency between impact and reactive peak in grip force was longer for the cerebellar patients (112±14 ms) than for the normal subjects (90±9 ms); P<0.02. The amount of reactive grip force did not differ significantly between patients (1.5±0.9 N) and normal subjects (1.7±0.8 N).

The additional delay due to cerebellar damage was also noted in the EMG data recorded at the first dorsal interosseous muscle. In particular, the onset of the EMG response was longer for the cerebellar patients (68±4 ms) than for the normal subjects (55±3 ms); $P<0.01$.

Discussion

An appropriate regulation of grip force is a necessity when objects are manipulated. Taking into account the delays in feedback control loops, it is recognized that feedforward commands provide a more effective and flexible setting which allows optimal control conditions for (partly) predictable circumstances. This strategy permits planning of appropriate response parameters prior to movement initiation as well as adjusting upcoming disturbances (Ghez et al. 1991; Stein and Glickstein 1992).

The present study examined anticipatory control of grip force during a drawer-opening task which involved a perturbing force that in its size depended on self-motion, i.e., how vigorously the drawer was pulled at impact. Due to the likely role of the cerebellum in anticipatory control strategies, the task was ideally suited to investigate proactive grip force control in cerebellar patients.

Preparatory actions in view of a predictable load perturbation

The data showed that normal subjects generated a characteristic grip force profile which consisted of two phases to secure drawer movement onset and to counteract the load pulse at the mechanical stop. The latter phase was characterized by an anticipatory grip force increase towards the predictable load perturbation at impact. These data on grip force adjustments are in line with previous observations in which impact forces are encountered during landing from a fall or jump (Dietz and Noth 1978; Melvill-Jones and Watt 1971) or during catching a ball (Johansson and Westling 1988; Lacquaniti and Maioli 1989).

Cerebellar patients developed an alternative control strategy to meet the goal requirements. In particular, grip force was raised to a high level around drawer movement onset while sustaining it until impact. Therefore, grip force was scaled to a default value which overestimated the required output. By overcompensating the grip force magnitude, these patients may seek to eliminate potential failures in movement control. According to Latash and Anson (1996), adaptive behavior during pathological conditions takes place due to modifications in the priorities of the central nervous system as new constraints are forced upon the movement system. Therefore, a less efficient strategy but a more secure one may be selected to accomplish the movement goal. In this respect, it can be suggested that the predictive modification of grip with respect to load force as observed in normals may have the advantage of economy of effort (Johansson and Westling 1984) and a refined ability to anticipate changes in load force (Flanagan et al. 1993).

The present findings also revealed that the cerebellar patients showed an increased grip-load force ratio as compared to the normal subjects, suggesting that they were unable to adjust and to scale the grip force according to the generated load force. It is also indicative of a higher safety margin and can in the first instance be related to a reduction in anticipatory behavior due to cerebellar dysfunction. These data extend observations from Müller and Dichgans (1994a, 1994b), who noticed a deficiency in the parameterization of grip force when cerebellar patients lifted objects of different weights. A change in anticipatory behavior resulting from cerebellar damage was also noted by Haggard et al. (1994). The authors observed increased grip apertures during a reaching task and suggested that this adaptive control strategy compensated for difficulties of hand transport.

Reactive adjustments after impact

Due to a perturbation, multiple receptors are activated which result in corrective reflex-like responses. For the present task EMG latencies were around 60 ms, suggesting that polysynaptic pathways were involved. The latency of this activity conforms with a long-loop reflex that may be transferred, at least in part, via the cortex (e.g., Jenner and Stephens 1982; Wiesendanger and Miles 1982). Furthermore, the significance of supraspinal control for reactive hand activity is emphasized by the high degree of representation of the wrist and fingers in the motor/sensory cortex and the cerebellum (Smith 1990).

That cerebellar dysfunction induced an extra delay in the reflex-like responses hints at an involvement of the cerebellum. This phase lag might arise from a delayed synaptic transmission or the use of alternative pathways. Likewise, the reactive grip force increase was prolonged in the patients, indicating an impairment in force build-up to restore the output. It is noteworthy that the functional importance of these reactive responses is limited in the present task as they occur too late to prevent slipping/loss of the drawer's handle at the moment of impact (i.e., the grip-load force ratio suddenly drops to a minimum prior to the appearance of the grip force response). However, it is conceivable that the cerebellar patients used an increased safety margin due to an overall adaptive strategy for coping with delayed reactive mechanisms. The latter is relevant when the brief delay between slipping of the object and updating of the force output becomes significant to maintain grasp stability.

In conclusion, the present results demonstrate that normal subjects and cerebellar patients employed different control strategies for opening a drawer with a predictable load pulse arresting the pulling movement. Whereas normal subjects used an anticipatory strategy during which grip force was adequately tuned to the load perturbation, cerebellar patients favored an alternative strategy during which an elevated grip force was generated from the beginning to the end of the task. Adopting this strategy might be the consequence of a failure to predict events adequately, resulting from any part of the anticipatory circuit including the cerebellum and/or impaired reactive mechanisms.

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