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RESEARCH NOTE

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Impaired anticipatory finger grip-force adjustments in a case of cerebellar degeneration

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Abstract We describe adjustments in grip force as a consequence of fluctuations in inertial load force during vertical movements of the upper limb in a patient with cerebellar degeneration. Normally grip force is adapted to load-force fluctuations, in particular to the maximum load force, which occurs early in upward movements and late in downward movements. Increased grip force during movement was observed in the patient, but the timing of maximum grip force was not different between upward and downward movements. This suggests impaired cerebellar prediction of the dynamic consequences of voluntary movement.

Key words Motor control · Grip force · Cerebellar · Predictive

Introduction

When using precision grip to hold an object with the thumb and finger on each side, the grip force (GF) normal to the surfaces must be sufficient for developing a frictional force to counter the load force (LF) tangential to the surface due to gravity. In lifting an object from a supporting surface, GF rises in parallel with (and may be said to anticipate) the rise in LF (Johansson and Westling 1984; for a review, see Johansson 1996). If arm movement is used to transport an object held in a precision grip, accelerations and decelerations may induce fluctuating inertial LFs in addition to LF due to gravity. In this case, studies with normal subjects have shown that GF rises prior to or simultaneously with LF due to movement, and maximum GF coincides with maximum LF (Flanagan et al. 1993; for a review, see Wing 1996).

In vertical movements, the summation of inertial LF with LF due to gravity results in a maximum in LF, which occurs earlier or later, depending on whether the movement is up or down. Here also, it has been found that maximum GF occurs at the time of maximum LF. However, the initial increase in GF is typically delayed in downward movement (Flanagan et al. 1993; Flanagan and Wing 1993; Flanagan and Tresilian 1994). Such anticipatory modulations of GF imply that people are able to predict, and thus plan for, the LFs due to voluntary movement, and it has been suggested that this may involve an internal forward model of limb dynamics (Flanagan and Wing 1997).

It has been proposed that control of hand trajectory involves an internal model, in the cerebellum, of the inverse transformation from hand to joint space (Kawato et al. 1987) or of the forward transformation from muscle commands to movement consequences (Miall et al. 1993) or paired inverse and forward models (Wolpert et al. 1998). Bastian et al. (1996) reported that ataxic upper-limb movements in cerebellar patients are due to impaired anticipatory compensation of interaction torques. This impairment could be due to a flawed internal model of limb dynamics in the cerebellum.

The internal model allowing predictive control of GF based on anticipation of LF may also be a cerebellar function. Müller and Dichgans (1994a) recently studied GF in 21 patients with cerebellar lesions. The task involved lifting an object and then holding it steady for 4 s. Results showed that the patients were capable of adjusting their GF as a function of the LF associated with objects of different weight. However, the coordination between GF and LF was altered in timing, suggesting impaired anticipation of their own lifting action. In a second study, Müller and Dichgans (1994b) used the same task to test two patients with a unilateral cerebellar lesion. In this study, they showed selective impairment of GF coordination with LF on the affected side. Müller

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and Dichgans' results suggest that cerebellar damage results in difficulty in programming GF appropriate to LF in lifting. In this paper, we ask whether there is a problem in GF adjustment for LF due to movement. Inertial LFs arising from movement occur in varying relations to LF due to gravity. This may create a special problem for cerebellar patients controlling upward versus downward movements if they have difficulty in predicting the outcome of movement due to an impaired forward model.

Maintaining a stable grasp on an object during movement requires that GF be related to other factors as well as LF. For example, GF needs to be scaled up if friction between the digits and the object is lower, as can occur with a smooth surface. Scaling of GF is observed both in lifting (Johansson and Westling 1984) and moving objects (Flanagan and Wing 1995). Studies on monkeys demonstrate that, when an animal has to lift and hold an object, the frequency of discharge of cerebellar Purkinje cells encodes the weight and/or the friction of the object. This effect is observed during the lift-off period while movement is performed, but also, and more importantly, prior to the application of GF and LF. These data suggest that the cerebellum plays a role in anticipating and controlling GF as a function of visible characteristics of the object (Espinoza and Smith 1990; Dugas and Smith 1992; Smith et al. 1993). Thus, it might be expected that anticipatory adjustments of GF for object surface characteristics should be abnormal in the presence of cerebellar lesions. We present a case study of a patient with cerebellar degeneration, who was asked to make up and down movements while holding an object with a smooth or rough surface.

Materials and methods

Subjects

We tested two right-handed control subjects (N1, N2; aged 47 and 51 years; both female) with no history of neurological disease and one patient (CE; aged 31 years, male) with a degenerative cerebellar atrophy due to a genetic disease diagnosed two years earlier. CE's neurological examination revealed cerebellar ataxia, difficulty in walking, oculomotor disorders, and some involuntary movements while at rest. No muscular weakness of the hands was found and reaching for a target was performed accurately.

Apparatus

Subjects grasped a cylindrical force transducer (Novatech, model 241) with the tips of the thumb and index finger placed on flat plates at either end (see Flanagan and Wing 1993). The surface of the plates was covered with a smooth wood veneer or fine grit sandpaper (resulting in lower or higher friction coefficients). The center of mass of the transducer (0.26 kg) was halfway between the points at which the digits contacted the transducer. The acceleration was measured with an accelerometer (Entran, model EGB-125-10D) mounted on the force transducer. A 12-bit, analog-to-digital interface board (National Instruments, model DAQ700) was used with a PC computer to collect and store grip-force and acceleration data sampled at 200 Hz. The raw force and acceleration data were digitally filtered using a fourth-order, zero-phase lag, low-pass Butterworth filter with a cut-off frequency of 20 Hz.

Procedure

The task involved the seated subject holding the transducer in a precision grip and moving the hand vertically up or down a distance of about 40 cm. Subjects were instructed to move the transducer in a straight vertical line using two marks on the wall beyond as approximate guides and to keep its orientation constant throughout the task. In combination with the smooth- and rough-textured surfaces, this created four experimental conditions: up-smooth, up-rough, down-smooth, down-rough. Ten to fifteen trials were run in each condition. To control the speed of movement, subjects made each movement following two sound signals of a metronome set at 2 Hz, the first sound indicating to the subject when movement should begin and the second when it should stop. The experimenter visually monitored subjects' movements on each trial to encourage compliance with the instructions.

Results

We first present average waveform data and, then, provide a statistical treatment in terms of quantitative measures of single-trial features. The upper part of Fig. 1 shows the coordination between GF and acceleration for smooth and rough surfaces in the up and down movement for the control subject N2. The thick black (thin gray) lines correspond to the mean (± 1 standard deviation), respectively. In both upward and downward movements, GF was modulated in phase with acceleration. The major increase in GF occurred when the acceleration increased, near the beginning of the upward movements and near the end of the downward movements. Thus, GF and acceleration traces reached their maximum values at approximately the same time.

The lower part of Fig. 1 shows the performance of the cerebellar patient. Overall levels of acceleration were somewhat higher (and ranged more widely) than was the case for the control subject. GF increased with LF, suggesting anticipatory adjustment, but the GF changes were not clearly synchronized with the maxima in acceleration; in particular, there appeared to be little differentiation between timing of GF functions associated with upward and downward movements.

Computer-aided measurement of features on individual trials resulted in the measures shown in Table 1: premovement baseline GF, maximum (minimum) acceleration, maximum GF, the ratio of GF to LF (where LF was computed as object weight plus the product of mass and acceleration) at maximum acceleration, the asynchrony between initial rise in GF and rise (decrease) in acceleration, and the asynchrony between maximum GF and maximum acceleration. As is apparent in Fig. 1, the cerebellar patient's movements resulted in somewhat higher levels of maximum (minimum) acceleration. Higher values of acceleration, producing higher LF, are normally associated with higher GF. The values in the table are, therefore, based on a subset of approximately one half of the patient's trials, selected so that the maximum (minimum) values of acceleration would be approximately equal to the control subject's maximum values. The mean absolute values of approximately 10 m/s/s thus obtained corresponded to the object being double its static

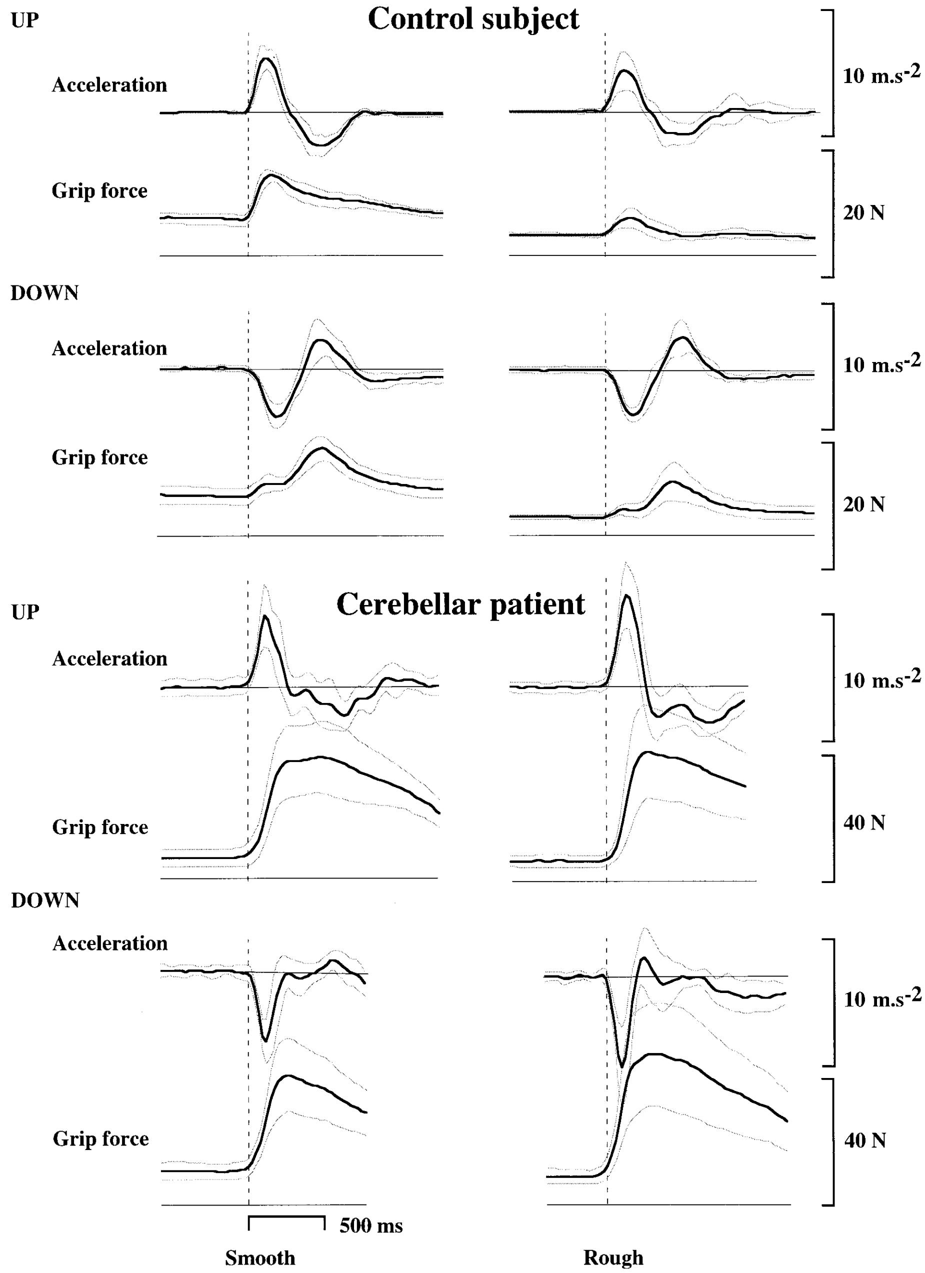

Fig. 1 Coordination between hand vertical acceleration (positive up) and grip force for the control subject N2 (*above*) and the cerebellar atrophy subject CE (*below*). Average functions (*bold lines*) ± one standard deviation (*gray lines*). Maximum grip force aligns with maximum acceleration in upward and downward movements for the control subjects, but not for the cerebellar patient

weight on positive peaks and weightless on negative acceleration peaks.

Separate three-way analyses of variance (ANOVA) with subject, movement direction, and surface roughness as factors were performed on the various measures of performance in Table 1 with P levels of 0.01 or less taken as statistically reliable. ANOVA revealed reliable main effects of subject on all factors [$F(2, 108)$, ranging from 6.06 to 122.05]. There were reliable main effects of surface textures; higher baseline GF [$F(1, 108)=7.6$] and higher maximum GF [$F(1, 108)=6.96$] with the smooth surface. Movement direction had reliable effects on GF/LF ratio [$F(1, 108)=15.57$], GF-acceleration onset asynchrony [$F(1, 108)=9.37$], and GF-acceleration maximum asynchrony [$F(1, 108)=44.44$]. These were qualified by reliable subject-by-direction interactions; GF/LF ratio [$F(2, 108)=11.02$], GF-acceleration onset asynchrony [$F(2, 108)=8.79$], and GF-acceleration maximum asynchrony [$F(2, 108)=27.43$] as well as by one reliable three-way subject-by-direction-by-surface interaction for GF-acceleration onset asynchrony [$F(2, 108)=5.80$]. We now detail these interactions by reference to the values in Table 1.

Grip force

Baseline GF was greater for the smoother surface in one of the two controls and in the cerebellar patient. Maximum GF was greater for smooth than for rough for all

Table 1 Measures of grip force (*GF*), load force (*LF*) and acceleration (*accel*) for two normal control subjects (*N1*, *N2*) and for the patient with cerebellar atrophy (*CE*). Mean latency (*bold values*) and standard deviation for each condition. A positive value of asynchrony indicates that grip force begins or reaches the maxima after the acceleration, a negative value indicates that grip force begins or reaches the maxima before the acceleration. *sub* Subject, *dir* direction, *smooth* smooth surface, *rough* rough surface

sub	dir	Baseline GF (N)		Accel (m/s/s) max (up), min (down)		Maximum GF (N)		GF/LF ratio at max Accel		Asynchrony (s) GF onset – Accel onset		Asynchrony (s) max GF – max Accel	
		smooth	rough	smooth	rough	smooth	rough	smooth	rough	smooth	rough	smooth	rough
N1	up	**5.7**	**6.2**	**9.7**	**10.3**	**13.1**	**10.8**	**0.39**	**0.31**	**0.013**	**0.017**	**0.017**	**0.017**
		1.2	2.2	1.6	3.5	1.1	2.5	0.06	0.05	0.017	0.016	0.018	0.045
	down	**5.5**	**8.3**	**–8.7**	**–10.1**	**14.0**	**13.3**	**0.53**	**0.45**	**0.115**	**0.165**	**0.025**	**0.003**
		2.3	2.9	0.7	1.5	2.5	2.0	0.09	0.13	0.148	0.182	0.061	0.089
N2	up	**6.1**	**3.3**	**9.6**	**7.9**	**13.1**	**6.2**	**0.41**	**0.23**	**0.025**	**0.002**	**0.031**	**0.029**
		1.0	0.3	2.3	1.9	1.4	1.3	0.08	0.04	0.015	0.051	0.032	0.022
	down	**6.3**	**3.1**	**–8.3**	**–7.8**	**14.2**	**9.0**	**0.80**	**0.41**	**0.082**	**0.096**	**0.015**	**–0.065**
		1.6	0.3	1.6	1.1	1.8	3.1	0.40	0.08	0.119	0.135	0.069	0.059
CE	up	**7.1**	**6.0**	**10.4**	**12.8**	**39.5**	**32.1**	**1.13**	**0.71**	**–0.010**	**0.006**	**0.336**	**0.223**
		3.2	1.8	2.3	1.3	12.2	12.1	0.44	0.25	0.053	0.019	0.219	0.123
	down	**8.0**	**5.2**	**–10.9**	**–11.2**	**36.0**	**35.8**	**5.58**	**4.67**	**–0.041**	**–0.058**	**–0.177**	**–0.022**
		3.1	1.8	2.6	2.2	13.8	15.7	6.42	4.42	0.032	0.070	0.174	0.205

subjects. However, maximum GF values were very much higher in the cerebellar patient. The ratio of GF to LF (computed as object weight plus the product of mass and acceleration) at maximum acceleration was consistently greater in the cerebellar patient, especially in the case of downward movements.

Timing

Both control subjects exhibited an early maximum in GF when moving downwards and a late maximum when moving upwards. The asynchronies in initial change in GF and acceleration were, thus, near zero in moving up, but large and positive in moving down. In most cases, the asynchronies in maxima of the control subjects were small. In contrast, the cerebellar patient exhibited early GF onset in downward movements, resulting in negative asynchronies in initial change in GF and acceleration. Moreover, there were large delays between maximum GF and maximum acceleration, positive in the case of upward movement and negative in the case of downward movement. Overall, the timing data suggest the GF adjustments by the cerebellar patient failed to differentiate between the contrasting times of maximum LF in upward and downward movements.

Discussion

The pattern of GF adjustments for LF fluctuations in upward and downward movements that we observed in the normal controls was consistent with previous results (e.g., Flanagan et al. 1993). Specifically, grip force rose later after movement onset when moving downwards than when moving upwards. And maximum grip force occurred at the same time as maximum load force, which occurred early in upward movements and late in downward movements. Such matching of GF adjustments to the form of the LF function suggests prediction of movement outcome, which could be based on an internal forward model of limb dynamics (Flanagan and Wing 1997).

In the present study, the cerebellar patient modulated GF during upward and downward movement. However, the pattern of GF adjustments did not differentiate between upward and downward movements. Instead, grip force rose with or before the onset of movement, whether up or down, and attained a maximum that was later than the maximum LF when moving upwards and earlier than the maximum when moving downwards. One possible reason for this changed pattern of GF adjustment is that the patient's prediction of the forthcoming movement was impaired. If such prediction is based on a forward model of limb dynamics, it implies that the forward model is implemented in the cerebellum, as suggested by Miall, Wolpert, and colleagues (Miall et al. 1993; Wolpert et al. 1998). However, effects of surface roughness on GF were observed in the cerebellar patient that were similar to those seen in the normal controls. This raises the interesting possibility that aspects of GF control related to object characteristics (as opposed to limb dynamics) are implemented outside of the cerebellum.

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