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RESEARCH ARTICLE

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Anticipatory postural adjustments in stance and grip

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Abstract The reactive forces and torques associated with moving a hand-held object between two points are potentially destabilising, both for the object's position in the hand and for body posture. Previous work has demonstrated that there are increases in grip force ahead of arm motion that contribute to object stability in the hand. Other studies have shown that early postural adjustments in the legs and trunk minimise the potential perturbing effects on body posture of rapid voluntary arm movement. This paper documents the concurrent evolution of grip force and postural adjustments in anticipation of dynamic and static loads. Subjects held a manipulandum in precision grasp between thumb and index finger and pulled or pushed either a dynamic or a fixed load horizontally towards or away from the body (the grasp axis was orthogonal to the line of the load force). A force plate measured ground reaction torques, and force transducers in the manipulandum measured the load (tangential) and grip (normal) forces acting on the thumb and finger. In all conditions, increases in grip force and ground reaction torque preceded any detectable rise in load force. Rates of change of grip force and ground reaction torque were correlated, even after partialling out a common dependence on load force rate. Moreover, grip force and ground reaction torque rates at the onset of load force were correlated. These results imply the operation of motor planning processes that include anticipation of the dynamic consequences of voluntary action.

Key words Posture · Arm movement · Hand grip force · Load force · Anticipation · Human

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Introduction

Unpredictable forces that disturb equilibrium in standing produce automatic, coordinated responses of muscles across a number of body segments that serve to restore body posture. These responses occur at a latency of 70–110 ms in the lower extremities (Nashner 1977). This is longer than the time required for a segmental spinal reflex but faster than a voluntary response to support surface perturbation (Nashner and Cordo 1981) and is thought to include supraspinal, possibly cortical, pathways (Matthews 1991). Suprasegmental influences presumably underlie the fact that automatic postural responses are not wholly shaped by the characteristics of the eliciting stimulus. For example, the responses change adaptively after change in type of surface motion or support surface configuration (Nashner 1976; Horak and Nashner 1986). Further evidence of central influences on automatic postural responses comes from the finding that the response is dependent on subject expectancy. For example, Horak et al. (1989) manipulated central set by exposing subjects to a range of platform perturbation velocities or amplitudes under blocked or random conditions. They found that there was scaling of the initial agonist integrated EMG and associated ground reaction torque response in the blocked amplitude condition which disappeared when perturbation amplitudes were randomized. This suggests that the initial magnitude of postural responses is centrally set to anticipated postural perturbation amplitudes based on experience with the stimulus built up over a series of trials.

The focus of postural studies is often on muscles of the lower limbs and trunk; however, under appropriate conditions, involvement of the muscles of the upper limbs may also be seen. For example, if a perturbation affecting standing balance is delivered when the hand is in contact with a fixed support, the automatic postural response includes activation of muscles of the arm and hand to help restore equilibrium (Cordo and Nashner 1982; Marsden et al. 1981). Thus, in resisting unexpected perturbations, motor pathways controlling arm and hand movement, which would normally contribute to fine manipulative functions of the upper limb, can be functionally linked with motor systems subserving whole-body postural stability. Including the upper limb in analysing postural responses has provided further evidence of their adaptability to biomechanical context and task goals. For example, Marsden et al. (1981) contrasted use of the upper limb in stabilising body posture when holding a fixed support with maintaining hand position in space when holding a cup of tea. Compared with taking support from a stable grasp point, steadying the cup involves a different pattern of arm muscle response in order to avoid transmitting the perturbation to the cup and spilling the tea.

Links between regulation of body posture and upper limb control have also been studied where voluntary arm movements produce disturbance to balance that is predictable. Bouisset and Zattara (1981), extending the pioneering work of Belenkii et al. (1967), demonstrated the presence of specific patterns of accelerations in the trunk and lower limbs prior to the onset of rapid arm movement. These they termed anticipatory postural adjustments (APAs). Bouisset and Zattara argued that the forward and upward acceleration of the body centre of mass produced by APAs serves to counter a backward and downward acceleration of the body centre of mass induced by the reaction forces of the arm movement on the shoulder. Thus it may be supposed that APAs reflect a central nervous system (CNS) strategy of compensating for the potentially destabilising reaction forces associated with voluntary arm movement (see also Friedli et al. 1988). Subsequent accelerometry (Zattara and Bouisset 1983; see also Bouisset 1991) and electromyographic (EMG) studies (Horak et al. 1984) have shown that the amplitude of APAs scale with the degree to which the arm movement disturbs posture (e.g. owing to loading of the limb). These results imply that the CNS is able to predict the magnitude of reaction forces and so compensate in advance.

Anticipatory adjustments for movement reaction forces have been demonstrated in the hand. When holding an object in a precision grip with the pads of the thumb and index finger against the sides, force normal to the grip surfaces allows a frictional force tangential to the surface to be developed that can counter load force due to gravity. If grip force is insufficient for the tangential load force and the frictional conditions, the object will slip. In lifting an object off a surface, load force increases until it matches the object's weight, at which point any further increase in load force results in movement off the surface. Johansson and Westling (1984) have shown that grip force changes during lifting occur in parallel with changes in load force. This suggests grip force changes are predictive of load force. Similar predictive coupling of grip force and load force has been shown for pulling and pushing static loads (Johansson et al. 1992).

Recently, Flanagan and coworkers (Flanagan et al. 1993; Flanagan and Wing 1993, 1995; for a review, see Wing 1996) have shown that when, in addition to gravity, there is inertial load force acting on the object owing to hand movement, grip force is elevated. They observed that changes in grip force are tightly coupled to the modulation of the inertial load. For example, in an upward arm movement, grip force starts to rise just before the load force begins to rise, reaches a peak that coincides with the peak in load force and declines as load force decreases. These results imply that the CNS anticipates the consequences of motor actions creating forces that are likely to disturb the stability, and hence the position in the hand, of a grasped object.

Thus, in both stance and grip, there are anticipatory motor adjustments involving coordinated activity of numerous muscles acting at several mechanically distinct body segments. These adjustments produce forces that compensate for destabilising forces, which may be of internal or external origin and which would otherwise disrupt the spatial relations among segments of the body and between the body and the environment. To what extent might there be common control processes for stance and grip, albeit at two different levels of scale? For example, suppose when carrying out the arm elevation task, used to demonstrate APAs, the subject is asked to hold an object in the hand. Since coordinated upper and lower limb responses are seen in reaction to unexpected perturbations, it might be that the predictable perturbation produced by raising the arm would invoke parallel anticipatory stabilization of the object (by modulation of grip force) and of the body (indexed by ground reaction forces and torques). In that case, if there is trial-to-trial fluctuation in the parameters of arm movement that causes variation in the effective perturbation, there might be covariation in body posture and grip adjustments, suggesting a common computation underlying the functional synergy.

In this paper we describe an experiment in which we examine the relation between grip force and ground reaction torques when subjects made horizontal parasagittal hand movements. They pushed or pulled a manipulandum that, in one condition ("dynamic"), was linked to an inertial load or, in the other condition ("static"), was fixed. In these situations the subject generated his or her own perturbation to balance and to the stability of the grip on the manipulandum. We were interested in whether there would be parallel adjustments of posture and grip evident in ground reaction torques and grip force. In order to determine an anticipatory basis to such adjustments, our analyses focus on first derivatives of forces and torques. Since maximum rates of change of force or torque must occur earlier than maximum force or torque, it makes it unlikely that the former could be set on the basis of concurrent feedback. More probably they reflect anticipatory mechanisms and we use correlational analyses to determine whether they have a common basis in compensating for the expected load force due to the arm action.

Materials and methods

Four right-handed subjects aged 22 to 46 years gave their informed consent and took part in the experiment, which had the approval of the local ethical committee on testing human subjects. One subject (S4) was female. Subjects S1 and S2 were the first two authors.

The subject stood with feet slightly apart on a force-torque plate (Bertec Corporation; model 4060H) that registered the three forces (F_x, F_y, F_z) and three moments (M_x, M_y, M_z) about its centre (see Fig. 1). The subject faced a waist-high, two-axis linear motor (Linear Technology; model LDU25/HD/01). The *y*-axis of this motor was oriented left to right producing motion parallel to the frontal plane, and the *x*-axis produced forwards-backwards motion in a parasagittal plane aligned with the right shoulder. A two-dimensional (2D) force transducer (Novatech; model F232) was attached to the top surface of one end of the *x*-axis motor and aligned so that measured force components were oriented with motor *x*- and *y*-axes. The *y*-force readings were used in a servo control loop with zero force set point so that any *y*-axis force would result in movement with minimal resistance. A one-dimensional (1D) linear accelerometer (Entran; model EGB-125–10D) was mounted on the force transducer in line with the *x*-axis. In trials with movement, a software control loop simulated a moderate inertial *x*-axis load of approximately 3 kg. On static trials, no *x*-axis motion was possible.

On top of the 2D force transducer was mounted a 3D force transducer (Novatech; model F233). Parallel vertical plates (3 cm deep by 5 cm high and aligned with the motor *x*-axis) afforded grip surfaces 5 cm apart from which it was possible to determine the grip force (normal to the plates) and the load force (tangential to the plates). Subjects grasped this manipulandum in a precision pinch with the pads of the right thumb on one side and index and middle finger on the other (forearm midway between pronation and supination).

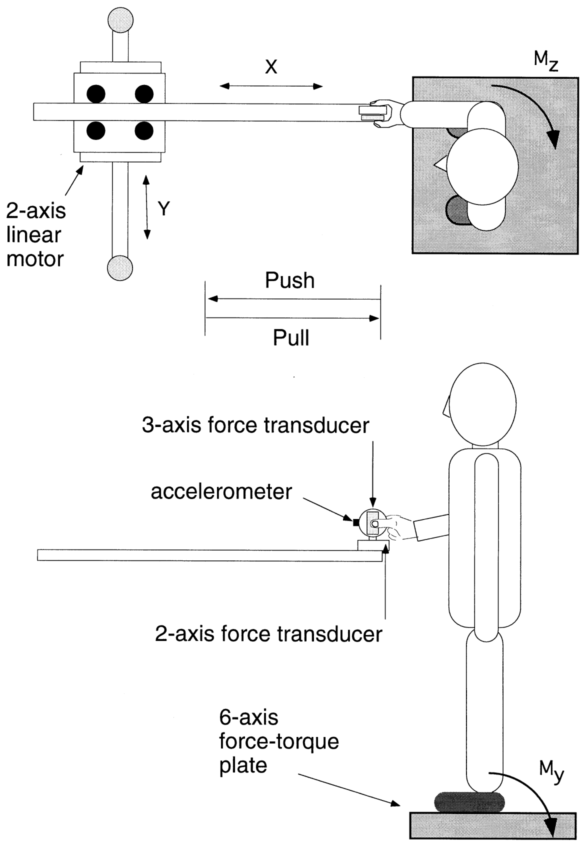

Fig. 1 Apparatus for measuring anticipatory adjustments of body posture (indexed by ground reaction torques produced by the subject standing on the force-torque plate) and grip (measured as the grip force between thumb and fingers) associated with push or pull movements (measured in terms of load force at the hand) against inertial (dynamic) or static loads provided by the linear motor

A MAC IIfx (Apple) computer with analog interface (National Instruments NB-MIO16X) sampled the six channels of ground reaction forces and moments, the five channels of force transducer information plus the *x*-axis position and acceleration at 375 Hz for a trial duration of 3 s. Data were subsequently digitally filtered (Butterworth fourth order, low-pass cut-off at 30 Hz).

The subject's task was, on alternate trials, to push and pull on the manipulandum after hearing an auditory cue. A block of trials comprised 20 push and 20 pull trials. In successive blocks, the *x*-axis linear motor was first free to move then locked static. In the block with dynamic trials the task was to produce a brisk 20- to 30-cm movement. In the block with static trials, the subject was required to produce a step increase in force and hold it steady for approximately 1 s before relaxing the force. Subjects were given several trials of practice in both conditions before data collection commenced.

Data processing

In examining the correspondence between anticipatory adjustments of posture and grip, we focused on load force (the *x*-translational force tending to move the manipulandum), grip force (normal to load force and stabilising the hand on the manipulandum) and ground reaction torque (contributing to stabilisation of posture) about the left-right (LR) horizontal axis (M_y) and the vertical axis (M_z).

An automated scoring routine was used to identify kinetic features relating to these variables and to their first-time derivatives (taken as successive sample differences). Measurements were checked by viewing the features as they were identified and, subsequently, by inspecting the times of the identified features. Separate statistical analyses (correlation, multiple regression) were carried out on each subject with replications defined by the 20 trials produced within each of the four conditions set by the combination of two directions (push compared with pull) and two classes of load (dynamic compared with static). In significance testing the *P*-level was set at 0.05.

Results

Figure 2 shows illustrative data in the form of single trials from each of the four subjects pushing (left) and pulling (right) the inertial load in the dynamic condition. The traces show (from the bottom) acceleration, load force, grip force, M_z and M_y. Although there is considerable variability between trials (subjects), temporal coupling between the various measures may be seen in the highlighted traces for S3. Since the load is primarily inertial, there is a close correspondence between the load force and acceleration traces, which indicates movement durations of 500–600 ms. Both sets of functions are biphasic, with the initial phase (acceleration) usually more sharply peaked than the second phase (deceleration). The initial peak in load force is generally attained by 200 ms after movement onset.

Grip force rises just before the onset of load force. There is some variation in form of the grip force function, with a single peak in some cases; in other cases, a

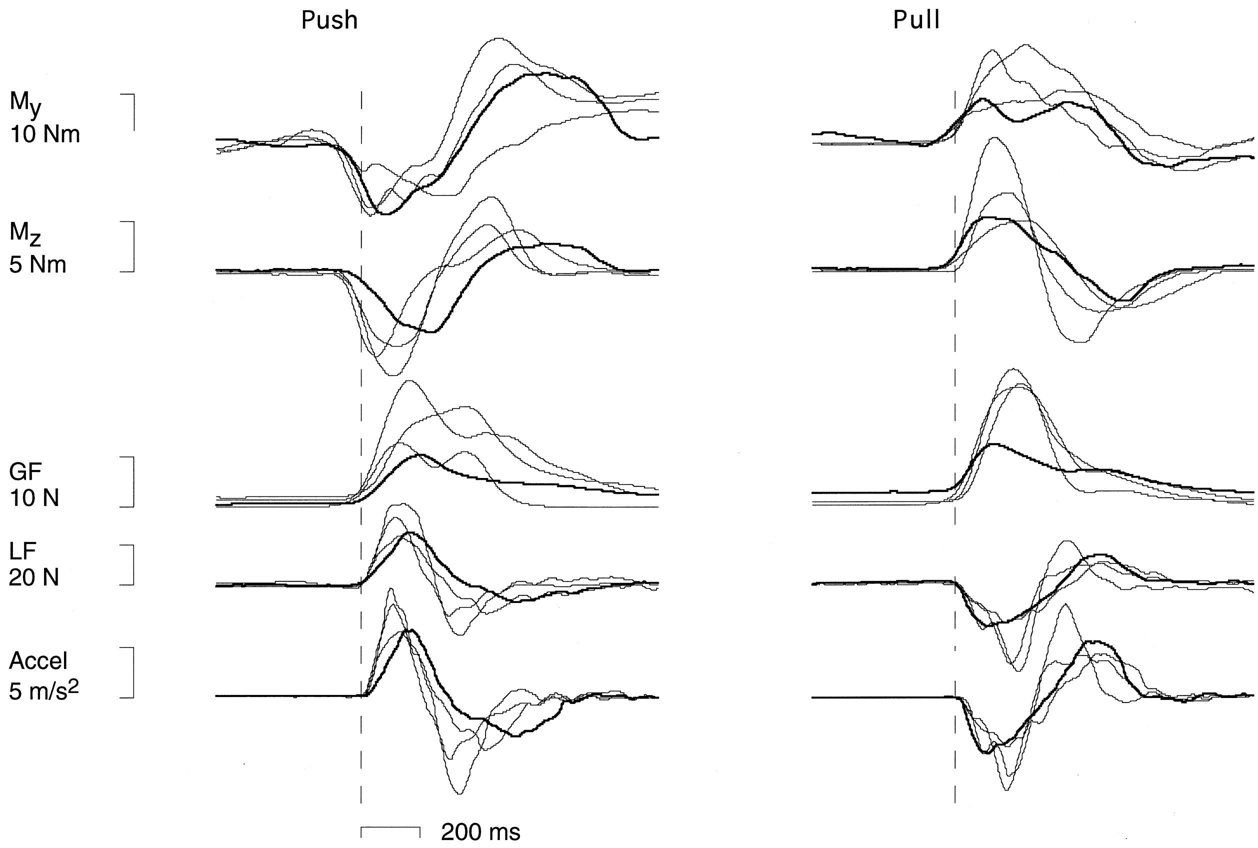

Fig. 2 Anticipatory adjustments of posture and grip associated with a dynamic inertial load. In push (*left*) or pull (*right*) movements, changes in ground reaction torque about the left-right (*LR*) horizontal axis (M_y) and vertical axis (M_z) and changes in grip force (*GF*) precede changes (marked with the *dashed vertical line*) in load (tangential) force (*LF*) and acceleration. Illustrative single-trial data from four subjects. The traces for subject S3 are *highlighted* to reveal the temporal correspondence between measures within a trial despite variability within a measure evident over trials

Table 1 Maximum absolute values of hand forces (LF load force, GF grip force) and ground reaction torques (M_y, M_z); means over four subjects

Variable	Condition			
	Dynamic		Static	
	Mean	SE	Mean	SE
LF (N)	29.5	0.7	35.9	0.7
GF (N)	20.0	0.6	19.6	0.6
M_y (Nm)	12.7	0.4	28.0	0.4
M_z (Nm)	7.1	0.2	5.9	0.2

major peak is preceded or followed by a minor peak (or at least a "shoulder"). Where two peaks are evident, both major and minor peaks are synchronised with peaks in load force. Grip force generally returns to the initial baseline after approximately 1 s, the decrease being less rapid than the initial rise. Ground reaction torque traces also depart from the baseline before the onset of load force. It will be observed that the initial changes in ground reaction torques are tightly coupled to the direction of load force (i.e. push compared with pull). The ground reaction torque traces are generally biphasic, more clearly so in the case of M_z.

Illustrative force and torque traces from static trials for each subject are shown in Fig. 3. Early changes in force and torque are seen, similar to those for the dynamic load, with direction of ground reaction torque change again tightly linked to the direction of load force. However, after a slight overshoot, the traces settle at a steady level for upwards of 1 s, after which the forces and torques drop back to baseline (in some of the traces, the beginnings of such decreases may be seen).

The mean peak values of the forces and torques and their times of occurrence are reported in Tables 1 and 2. Inspection reveals that load force and M_y were larger in the static than in the dynamic condition, whereas there was little difference in grip force and M_z. The times to peak values of the forces and torques were considerably later in the static condition compared with the dynamic condition.

The evaluation of the anticipatory nature of grip force and ground reaction torque in dynamic and static conditions is based on the first-time derivatives of the grip force, load force and ground reaction torque functions, which we abbreviate as dGF, dLF, dM_y and dM_z. Illustrative force and torque rate functions when S3 pushed the dynamic load are shown in Fig. 4. These

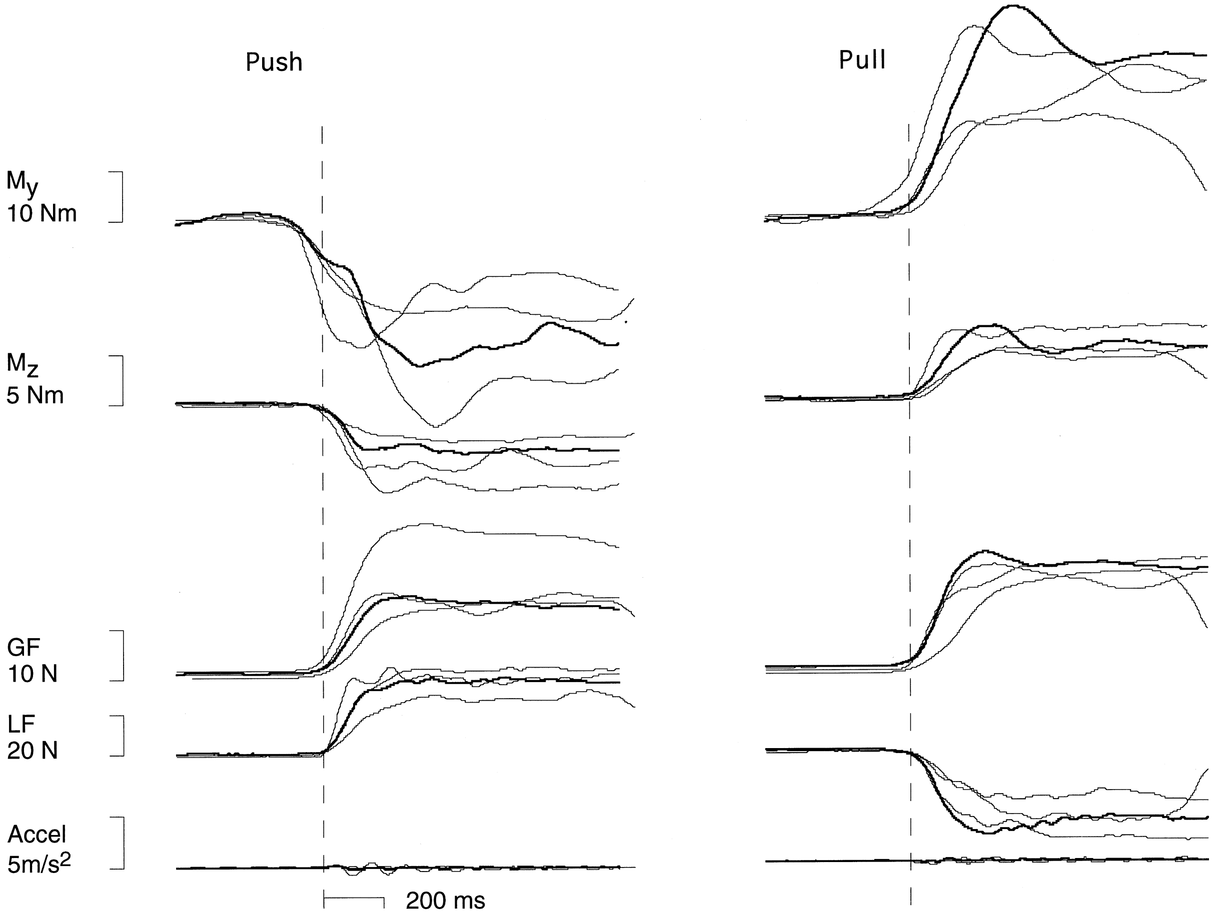

Fig. 3 Anticipatory adjustments of posture and grip associated with pushing (*left*) or pulling (*right*) on a static load. Changes in ground reaction torque about the LR horizontal axis (M_y) and vertical axis M_z and changes in grip force (*GF*) precede changes (marked with the *dashed vertical line*) in load force (*LF*; with negligible acceleration). Illustrative single-trial data from four subjects with traces for one subject, S3, *highlighted*

Table 2 Mean times (in ms relative to load force onset) of peak hand forces (load force, LF, and grip force, GF) and ground reaction torques (M_y and M_z); averages over four subjects (with standard errors)

Variable	Condition			
	Dynamic		Static	
	Mean	SE	Mean	SE
LF	177	3	366	3
GF	240	8	348	8
M_y	210	11	351	11
M_z	158	5	363	5

Table 3 Mean times (in ms relative to load force onset) of the times of onset and peak rates of change of grip force (dGF/dt), load force (dLF/dt) and ground reaction torque (dM_y/dt, dM_z/dt); average over four subjects (with standard errors)

Measure	Variable	Condition			
		Dynamic		Static	
		Mean	SE	Mean	SE
Onset time	dGF/dt	–47	1	–62	1
	dM_y/dt	–81	9	–55	5
	dM_z/dt	–40	1	–50	2
Peak time	dLF/dt	100	1	102	1
	dGF/dt	98	1	108	1
	dM_y/dt	49	8	80	8
	dM_z/dt	50	1	99	2

clearly show changes in dGF, dM_y, dM_z leading changes in dLF; mean lead times over all subjects are given in Table 3. The changes in force and torque rates culminate in local maxima (in terms of absolute values) and their times are also summarised in Table 3. Comparison with Table 2 shows, as would be expected, that the times to the peak values of the first derivatives were much less than the times to the peak values of the forces and torques. Peak values of dGF, dLF (and dM_y and dM_z in the static condition) were closely synchronised. In the dynamic condition, peak dM_y and dM_z occurred relatively early.

The peak values of dGF were positively correlated with the peak values of dLF and dM_y and dM_z, as may be seen in Table 4. (Peak dLF was also correlated with peak

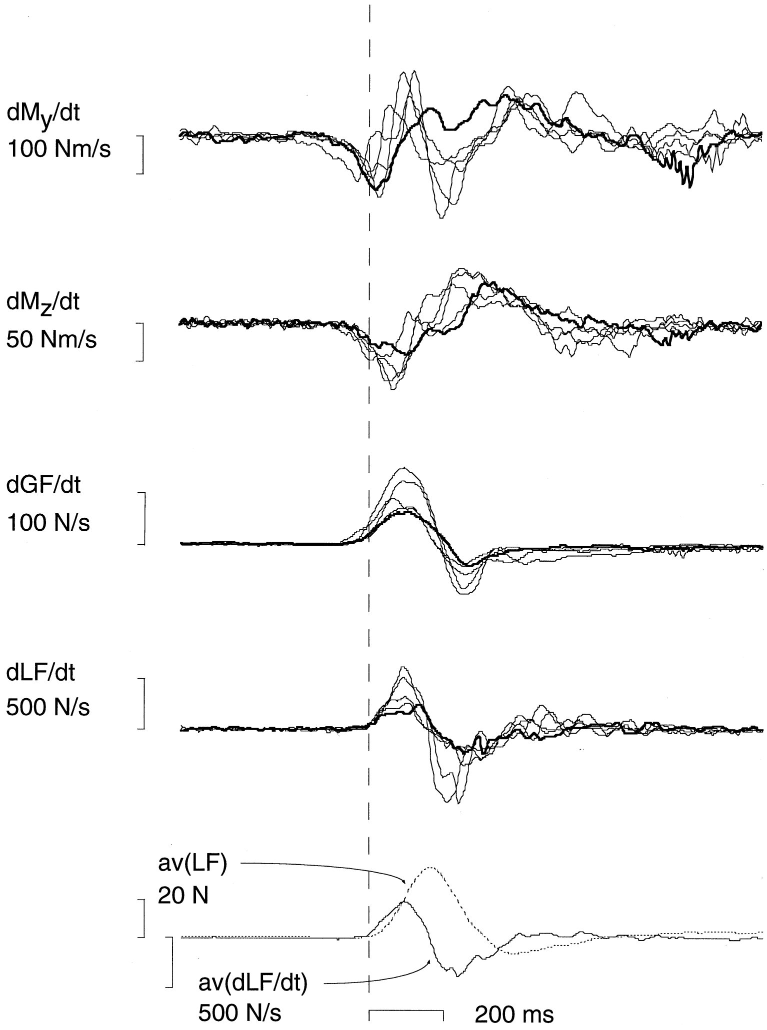

Fig. 4 Anticipatory adjustments of posture and grip are clearly evident in illustrative force and torque rate data from S3 moving the inertial load. Rate of change of ground reaction torque (*d*M_y and *d*M_z) and grip force (*dGF*) precede changes in load force rate (marked with the *dashed vertical line*) on five successive push trials. The *highlighted function* corresponds to the highlighted curve in Fig. 2 (left). The *two superimposed traces at the bottom* are the means (*av*) of the corresponding load force (*broken line*) and load force rate (*continuous line*) functions

Table 4 Correlations of peak rate of change of grip force with peak rates of change of load force (dLF) and ground reaction torques (dM_y,dM_z); ns indicates non-significant correlations

Subject	Condition					
	Dynamic			Static		
	dLF/dt	dM_y/dt	dM_z/dt	dLF/dt	dM_y/dt	dM_z/dt
1	0.87	0.47	0.69	0.58	0.33	0.24 ns
2	0.64	0.65	0.69	0.46	0.58	0.52
3	0.64	0.26 ns	0.45	0.51	0.48	0.24 ns
4	0.29 ns	0.28 ns	0.78	0.67	0.39	0.56
Mean	0.52	0.40	0.64	0.56	0.45	0.39

dM_y and dM_z; mean values in dynamic and static conditions were 0.50 and 0.41 for dM_y and 0.56 and 0.54 for dM_z.)

Because peak rates of change of force and torque occur early after load force onset, it seems unlikely that the correlations between dGF and the rates of change of ground reaction torque reflect the operation of feedback about load force. Instead it seems more likely that they reflect a common input to the processes underlying anticipatory grip and whole-body postural adjustments. However, another possibility is that the correlation arises from mechanical coupling of the arm with the ground via intervening trunk and limb segments. An argument against this last possibility is provided by stepwise linear regression analysis of dGF with dLF, dM_y and dM_z as predictor variables (condition was also included as a dummy variable). All subjects showed significant dependence of dGF on one or both of the ground reaction torque rates, even when dLF influence (where significant) was allowed for (see Table 5).

Further evidence of an anticipatory basis to the link between grip force and body postural adjustments comes

Table 5 Slope estimates for stepwise linear regression of rate of change of grip force by load force rate (dLF) and ground reaction torque rates (dM_y, dM_z). Cell entries marked ns indicate that the variable was not entered into the final equation. A dummy variable coding condition (dynamic vs static) was non-significant in all cases

Subject	dLF/dt	dM_y/dt	dM_z/dt
1	0.25	ns	0.54
2	ns	0.23	0.99
3	0.14	0.17	ns
4	ns	ns	1.60

Table 6 Correlations between rate of change of grip force and ground reaction torque rates (dM_y, dM_z) at load force rate onset; ns indicates non-significant correlations

Subject	Condition			
	Dynamic		Static	
	dM_y/dt	dM_z/dt	dM_y/dt	dM_z/dt
1	0.46	0.74	0.58	0.78
2	0.40	0.62	0.26 ns	0.28 ns
3	0.33	0.66	0.08 ns	0.39
4	0.39	0.47	0.20 ns	0.48
Mean	0.40	0.62	0.28	0.48

Table 7 Correlations between onset times (relative to load force rate onset) of grip force rate and ground reaction torque rates; ns indicates non-significant correlations

Subject	Condition			
	Dynamic		Static	
	dM_y/dt	dM_z/dt	dM_y/dt	dM_z/dt
1	0.07 ns	0.43	0.37	0.48
2	–0.04 ns	0.46	0.11 ns	0.45
3	0.53	0.42	0.31	0.27 ns
4	0.37	0.65	0.44	0.36
Mean	0.23	0.49	0.31	0.39

from the fact that consistently positive correlations were observed between dGF and ground reaction torque rates taken at dLF onset (see Table 6). At a point when the arm is producing no appreciable load force, there is nonetheless an important dependence betweeen dGF and dM_z and between dGF and dM_y.

There were also reliable positive correlations (see Table 7) between dGF onset time and ground reaction torque rate onset times (expressed relative to dLF onset).

Discussion

In previous reports we have shown that grip force adjustments anticipate fluctuations in inertial loads associated with rapid arm movements (Flanagan et al. 1993; Flanagan and Wing 1993, 1995). A tight coupling between grip force and load force is observed under a wide range of conditions (e.g. horizontal, upwards and downwards movements) where the pattern of inertial loading varies. Changes in the load force function result in adaptive changes in the form of the grip force function (Flanagan and Wing 1997). Moreover, a close link between grip force and load force has been described for pushes and pulls against static loads (Johansson et al. 1992).

The results presented in this paper confirm that adjustments in grip force anticipate both dynamic and static loads. Moreover, in the case of dynamic loads, we show that grip force anticipates load force when, prior to movement, the hand has not taken the weight of the object. In previous work (e.g. Flanagan et al. 1993), the transport movement has always been preceded by a period of steady holding. In principle, the sensory input in this phase of the task could be the basis on which the CNS, when planning transport, determines the factor necessary for scaling grip force to the object's inertia. That is, from trial to trial, the CNS might only maintain a value for object weight (as demonstrated by the work of Johansson and colleagues), but not for object mass. The scaling of grip force in the weightless environment of the actuator in the present experiment demonstrates that the CNS is able to maintain a value for object mass in the absence of weight information.

Taken together, these findings suggest that the CNS maintains an internal model of the dynamics of the motor apparatus and external load that is used to predict the load force acting on the hand (Flanagan et al. 1995; Flanagan and Wing 1997). This prediction would provide the basis for adjusting grip force during movement in order to stabilize the object and prevent it slipping. Such an internal model might also be used in the control of the arm movement to determine the motor commands required to attain the desired hand trajectory (see also Atkeson 1989; Uno et al. 1989; Miall et al. 1993; Wolpert et al. 1995). Our data do not address the development of this internal model. However, in the present experiment subjects were given several trials practicas in each condition prior to data collection. Other research with the same apparatus (Flanagan and Wing 1996) indicates this would have been sufficient for the subjects to develop an adequate internal model (and to determine the frictional characteristics of the grasp surfaces).

The use of an internal model to predict reaction forces is also suggested by the anticipatory postural adjustments associated with arm movements. The fact that APAs are sensitive to the magnitude and direction of the reaction forces indicates that these are predicted by the CNS in order to minimise their postural consequences (Bouisset and Zattara 1981; Friedli et al. 1988). Our results showing directed ground reaction torque changes preceding one-handed horizontal pushes and pulls confirm these findings. We have shown that peak rates of rise of ground reaction torque (dM_z or

dM_y) are positively correlated with the peak rate of rise of load force. Although this must partly reflect mechanics, it is probable that it also reflects central drive. Moreover the mechanical coupling itself will depend on stiffness of the kinematic chain between hand and feet, which may be modulated through centrally commanded muscle coactivation.

The main aim of this paper was to investigate the concurrent development of anticipatory grip force and body postural adjustments in one and the same arm movement. In particular, on the hypothesis that grip force and postural adjustments might share a common basis, we sought to determine whether they might be functionally linked across a variety of loads. To this end we examined pushes and pulls under static and dynamic conditions. Positive correlations were found between peak rates of change of grip force and ground reaction torque. These occurred sufficiently early after load force onset that the correlations are unlikely to have reflected adjustments based on feedback about load force rise. Rather, we consider that the correlations reflect anticipatory adjustment of grip and body posture based on a common source of information about the expected loads associated with the forthcoming planned arm movement.

For all four subjects, there was a reliable residual correlation between dGF and ground reaction torque rates after partialling out variation in load force rate. There were individual differences, with the dependence showing up in either, or both, of the ground reaction torque rates. Without a full postural model it is not possible to explain these differences. However, for present purposes, the important point is that the residual correlations suggest that further common variance is added following determination of the expected load force. One possible interpretation of this is that one and the same process determines body postural and grip force adjustments from the predicted load force. Alternatively it may be that transferring the prediction to separate mechanisms for posture and grip is subject to a common error.

In the motor control literature it is common to make contrasts between gross movements involving the whole body and the fine motor function of the hand. In demonstrating correlations between anticipatory adjustments to posture and grip, we have emphasised parallels between gross and fine components of motor control. Thus our work may be seen to extend that of others who have shown anticipatory postural adjustments involving the two arms (Viallet et al. 1992) and the index fingers of either hand (Kaluzny and Wiesendanger 1992).

Finally we note that, while grip force and ground reaction torque are functionally linked, grip force has a particular advantage over ground reaction torque as an index of the ability of the CNS to predict load. Because grip force acts orthogonally to the load, it does not contribute to the load force. In general this is not the case for ground reaction torque, so that load force changes in part reflect ground reaction torque changes and vice versa. This means that interpretation of the detailed form of the ground reaction torque function requires an explicit biomechanical model with full information about the all-body segments, whereas this is not the case for grip force.

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