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RESEARCH ARTICLE

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The stability of precision grip forces during cyclic arm movements with a hand-held load

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Abstract In this paper we examine the coordination of grip force and load during brisk cyclic arm movements with a hand-held object under a range of conditions. We show that, regardless of the surface texture of the object or movement frequency, grip force is modulated in parallel with load. Thus, the tight coupling between grip force and load observed in short-duration tasks such as lifting or point-to-point movements is also seen in longer-duration cyclic movements. Moreover, the gain of the relation between grip force and load remains essentially constant over time. Across conditions, we find a dissociation between the gain of the relation between grip force and load and the grip force offset. With a more slippery surface texture both the gain and offset increase, whereas increases in frequency lead to an increase in the offset but a decrease in gain. This suggests that these two parameters are under independent high-level control. We also observe that when subjects were instructed to maintain a high-baseline grip force during the movement, grip force was still modulated with load even though an increase in grip was not necessary to prevent slip. This suggests that there is an obligatory coupling between grip force and load. This coupling might be subserved by low-level mechanisms not under high-level control.

Key words Motor control · Precision grip force · Prehension · Cyclic arm movement · Human

Introduction

In order to lift, transport or manipulate an object held in the hand, the fingertip forces must be precisely controlled in order to perform the task while maintaining stability (e.g. avoiding slip). In a series of studies, Johansson and colleagues have shown that the control of grip forces in manipulation involves subtle interplay between anticipatory and sensory-based feedback mechanisms (see Johansson 1991 for a review). Sensory information, provided largely by skin afferents, is used to update anticipatory motor commands (see Johansson et al. 1992) and also subserves reflex-mediated increases in grip force following slip. The latter are critical when the programmed grip force is too low (Johansson and Westling 1988a) or when an unexpected load is encountered (Cole and Abbs 1988; Johansson and Westling 1987). However, in general, the anticipatory changes in grip force are finely tuned to the requirements of the task so that the system does not need to rely on reflex mechanisms. For example, Johansson and Westling (1984) have shown that when lifting an object held in a precision grip (with the tips of the index finger and thumb at its sides) the grip force normal to the object surface increases in parallel with the load force tangential to the surface. The maximum rate of change of grip force anticipates the final grip force, which depends both on the surface texture of the object and the load.

Recently, researchers have employed the tasks and methods developed by Johansson and Westling to examine the sensorimotor control of manipulation in the elderly (Cole 1991; Cole and Beck 1994), during development (Forssberg et al. 1991a,b), in patients with sensorimotor disturbances due to brain lesions (Hermsdörfer et al. 1992) and in monkeys (Picard and Smith 1992). There have also been studies of grip force changes with load force when pulling against an elastic load (Johansson and Westling 1984) or a ramp load (Johansson et al. 1992; Jones and Hunter 1992). Our own work has extended the principle of anticipatory control of grip force to arm movements with a hand-held load (Flanagan and Tresilian 1994; Flanagan and Wing 1993; Flanagan et al. 1993). We have shown that grip force modulates in phase with acceleration-dependent inertial load. In all of these cases, the fact that grip force tracks the loads indicates that the load is predicted. Indeed, this suggests that grip

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force might be taken as an index of motion planning. However, the question then arises as to whether the coupling of grip force and load is seen in all classes of movements. To date, studies of precision manipulation have focused on discrete tasks of limited duration such as lifting and point-to-point arm movements. However, continuous movements have not been studied in detail and it remains an open question whether a tight linkage between grip force and load is present.

In discrete lifting movements, Johansson and Westling (1984) have shown that grip force is modulated with load such that it is only a little above the minimum required to prevent slip. They suggested that grip force is modulated in order to economize effort. This implies that there is a cost associated with excess grip force and the goal is to minimize the grip while ensuring stability. However, under certain conditions, there may be a cost involved in modulating grip force. Thus, in continuous movements with many fluctuations in load (e.g. cyclic up-and-down motions of arm), the central nervous system (CNS) might adopt a strategy of maintaining an elevated grip force while limiting its modulation. Another possible reason for keeping grip force to a minimum might be if sensibility is enhanced at lower grip forces. However, in a case where there are continuous and predictable fluctuations in load (e.g. cyclic movements) and where the environmental conditions are constant, enhanced sensibility may not be so critical and hence modulation in grip force might be reduced. We have shown elsewhere that grip force is modulated in phase with load during cyclic movements (Flanagan and Tresilian 1994; Flanagan et al. 1993). However, we did not analyse the extent of modulation or whether it changes over time. Moreover, we did not study factors which might influence the modulation.

In this paper we systematically examine the coupling between grip force and load under a range of movement conditions. In the first experiment we recorded cyclic movements, made at a moderate rate, with objects with either rough or smooth contact surfaces. We varied the surface texture in part for generality but also to test whether there is a change in gain of the relationship between grip and load as is seen in lifting. In lifting with a more slippery object, both the overall grip force and the extent of modulation with load increase (Johansson and Westling 1984). An issue is whether, in cyclic movements, an overall greater grip force might be used with the more slippery surface in order that grip force modulation might be reduced. In the second experiment, we manipulate cycle frequency. With constant movement amplitude, increases in frequency lead to an increase in both the rate of change of load force and the magnitude of the loads. Again the issue is whether there are corresponding changes in grip force modulation or whether there are changes in overall grip force which limit the need for modulation. In the third experiment, we consider the effect of instructions to maintain an elevated baseline grip force during the cyclic movement. This elevation was high enough relative to the load forces encountered that modulation of grip force was not necessary to prevent slip. The question was whether grip force would nevertheless be modulated in phase with load.

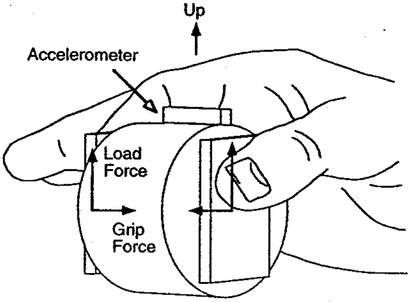

Fig. 1 Drawing of the force transducer and the configuration of the hand used to grasp it. An accelerometer, mounted on top of the transducer, measured the acceleration in the vertical direction

Materials and methods

Subjects

Four male subjects, including the authors, participated in all of the experiments. None of the subjects reported motor or sensory deficits. All used their preferred, right hands to grasp and move the object. The ages of the subjects ranged from 31 to 47 years. All subjects gave their informed consent prior to participating in the experiments and were told that they could discontinue at any time.

Apparatus

Subjects grasped a cylindrical force transducer (Novatech, model 241) with the tips of the thumb and index finger placed on flat plates on either side (see Fig. 1). The surface texture was either aluminium, satin or sandpaper. The mass of the transducer (0.26 kg) was centred halfway between the points at which the digits contacted the transducer. Thus, rotational torques were not induced by moving the object in a straight line. Linear acceleration was measured with an accelerometer (Entran, model EGB-125-10D) mounted on the force transducer.

Experimental procedure

Subjects made vertical, cyclic arm movements of about 30–40 cm in amplitude. The subjects were instructed to move the transducer in a straight line and to keep its orientation constant throughout. Movements were visually monitored by the experimenter to ensure that the subjects complied with these instructions.

The slip ratio was estimated by asking subjects to gradually reduce their grip force while holding the object stationary (Johansson and Westling 1984). The grip force measured at the moment at which the object slipped (as registered by the accelerometer) was taken as the slip force. The slip ratio is the ratio of slip force to the weight of the object (i.e. the load while holding the object stationary). Slip ratios were estimated for each subject and each surface texture.

Experiment 1. In the first experiment, we examined vertical cyclic movements of 30–40 cm made at a moderate rate. The effect of surface texture on grip-load coordination was examined. The contact surfaces of the transducer were covered with either satin (smooth) or sandpaper (rough). Six 5-s trials were collected for each subject: three per texture.

Experiment 2. The goal of this experiment was to examine the effects of movement rate on the coordination of grip force and load force. Subjects were instructed to produce vertical cyclical movements at one of three rates: slow, fast or very fast. This was achieved by varying the frequency of the movement while keeping the amplitude relatively constant (30–40 cm). Thus, faster movement rates were associated with greater amplitudes of load force modulation. The mean frequencies (averaged across trials and subjects) at the slower, faster and very fast rates were 1.43, 2.14 and 3.13 Hz, respectively. Three 5-s trials at each frequency were collected for each subject. The contact surfaces were aluminium.

Experiment 3. This experiment examined changes in grip-load coordination when subjects were instructed to raise the baseline level of grip force before and during the cyclic movements, 30–40 cm in amplitude. Thus, in this study the background grip level was varied intentionally, whereas, in the first two experiments, subjects adjusted the baseline grip level to meet the surface and load requirements. Nine 5-s trials were collected for each subject. In the first three trials, no instruction was given to the subject about grip force. This served as a control condition. In the next three trials subjects were asked to increase their grip force to a steady level 10–15 N above normal before initiating the movement and then maintain this overall level throughout. In the next three trials, subjects were asked to maintain an even higher grip force (20–25 N above the normal level). The contact surfaces were aluminium.

Data processing and analysis

Acceleration and grip force signals were sampled at 200 Hz and then digitally low-passed with a fourth-order, zero phase-lag Butterworth filter using a cut-off frequency of 14 Hz. Load force was defined as the sum of the inertial force (mass×acceleration) and gravitational force (mass×gravity). The force ratio was defined as the ratio of grip force to absolute load force.

In some trials there were gradual, low-frequency changes in grip force over time, which increased the variability in grip force and resulted in less reliable estimates of the slope of the grip-load function. Therefore, we applied a procedure to remove the low-frequency content in grip force before computing the slope and intercept using linear regression. The procedure involved three steps: (1) the initial second of the trial was removed; (2) the grip force was high-pass filtered with a cutoff frequency of 0.3 Hz (experiments 1 and 2) or 0.8 Hz (experiment 3); and (3) an offset was added so that the filtered grip force had the same mean as the unfiltered grip force. All of the slopes and intercepts reported in this paper were estimated after high-passing and offsetting grip force.

Results

In this section, we present plots of waveforms over time and plots of grip force versus load force. We also present the results of linear regression analyses on the relation between grip force and load.

Experiment 1: effects of surface texture

Here we describe the effects of object surface texture on the coordination of grip force and load force during vertical cyclic movements performed at a moderate frequency (1.6–1.8 Hz). The surface texture was either satin (smooth) or sandpaper (rough). Surface texture was varied in order to manipulate the coefficient of friction between the skin and object.

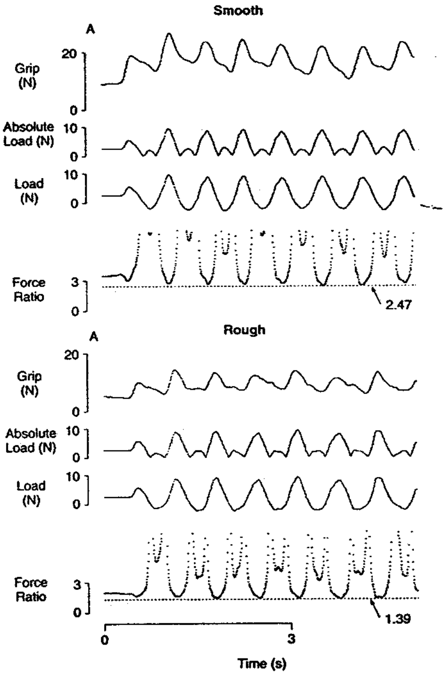

Fig. 2 Single records from subject A from vertical cyclic movements with either the smooth (*top*) or rough (*bottom*) object (experiment 1). The *dashed horizontal line* represents the minimum force ratio observed during the trial. The mean grip force and the extent of grip force modulation is greater for the more slippery smooth surface

Figure 2 shows a "smooth" and a "rough" trial for subject A. For each trial, four waveforms are shown (top to bottom): grip force, absolute load force, load force, and the force ratio. Because the force ratio tends towards infinity when the load force approaches zero, only force ratio values less than or equal to 8 have been plotted. The dashed horizontal line represents the minimum value of the force ratio observed during the trial. The load force has an offset due to gravitational loading and fluctuations due to inertial loading. As a result of this offset, the absolute load force features a series of large peaks (coinciding with acceleration maxima) interleaved with smaller peaks (coinciding with acceleration minima). In all subjects and in all trials, grip force and absolute load were coupled both in time and magnitude. For example, in the figure the large peaks in grip force coincide with the large absolute load force peaks and smaller grip force peaks – or at least "bulges" in grip force – coincide with the smaller absolute load force peaks. The cycle frequency and amplitude of acceleration are similar for the two textures. Thus, differences in the grip force functions can be largely attributed to the effects of surface texture and hence the friction between the skin and object.

Cross-correlations between grip force and absolute load were carried out for each of the six trials (three per texture) performed by each subject. The maximum correlations ranged from 0.71 to 0.94, with a mean of 0.85. The maximum correlations occurred at time lags ranging from –10 to 15 ms, with an a mean of –4.8 ms. (A positive lag indicates that the grip force led the absolute load force). These results support the observation that grip force and absolute load force are correlated in magnitude and are modulated in phase. The force ratio changes throughout each cycle. However, the minimum ratio in each cycle (coinciding with maximum load) is remarkably constant across cycles.

Both the overall level of grip force and the extent of grip force modulation were greater with the smooth surface. As a result, the minimum force ratios observed in each cycle were greater for the smooth surface. We computed the means and SDs of the minimum force ratio, averaged across cycles and trials, for each surface texture and for each of the four subjects. We also computed the means and SDs of maximum load. One-way ANOVAs were carried out for each subject separately to test for the effect of surface texture on the minimum force ratio and maximum load. For all four subjects, the minimum force ratio was significantly greater ($P<0.001$) with the smooth object (A, $F_{1,34}=470$; B, $F_{1,49}=36.8$; C, $F_{1,52}=168$; D, $F_{1,50}=271$). This effect was not due to differences in maximum load. For all subjects, the difference between the maximum load means for the rough and the smooth objects did not reach significance ($P>0.05$).

Figure 3 shows four plots of grip force against load force. Each set of traces shows a single trial with the smooth object (solid trace) and a single trial with the rough object (dashed trace) for a single subject. The load at the onset corresponds to the weight of the object (2.55 N). Note that grip force at the start of the movement is less than at equivalent loads during the movement. The single solid line and single dashed line represent the slip force as a function of load for the smooth and rough objects, respectively. The slope of the slip force line, or slip ratio, was estimated for each subject and texture (see Materials and methods). The slip ratio is greater for the smooth surface for all subjects. However, the difference between the smooth and rough slip ratios varies from subject to subject. This may partly reflect individual differences in sweating rate (Westling and Johansson 1984).

Grip force tends to increase as load increases or decreases from zero. However, because the load is positive during almost the entire movement cycle, we have focused on the relation between grip force and positive load values. Linear regression analysis was used to determine the slope and intercept of the relation between grip force (after filtering as described in Materials and methods) and positive values of load force for each texture. Separate regressions were carried out for each subject. A single slope was estimated for each surface texture, while allowing different intercepts for each of the three trials per texture. Table 1 presents the slope and range of intercepts for both surface textures and for each subject. In addition, the slip ratio for each subject and texture is shown. With the exception of C, the grip-load slope for the smooth surface was significantly greater than the slope for the rough surface ($P<0.001$). Also, with the exception of B, the intercepts of the smooth trials were all greater than any of the intercepts of the rough trials. Thus, both the slope and intercept of the best-fit straight-line relation between grip force and load are generally greater when moving the smooth object than when moving the rough object. The larger slope generally observed for the smooth object is associated with a larger slip ratio.

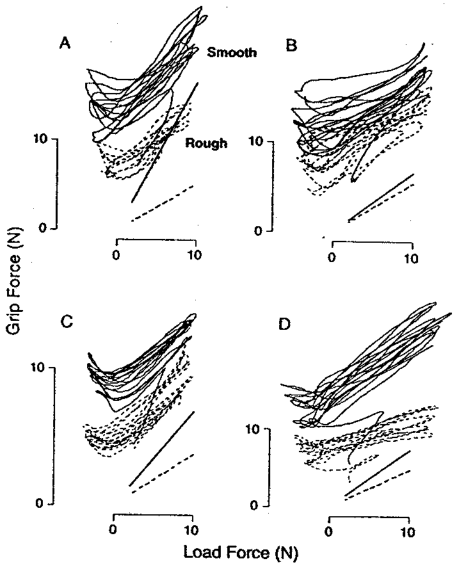

Fig. 3 Plots of grip force versus load for each subject in experiment 1. Each plot shows one trial with the smooth object (*solid trace*) and one with the rough object (*dashed trace*). The *solid lines* and *dashed straight lines* represent the slip forces for the smooth and rough objects, respectively. In general, both the slope and intercept increase with surface slipperiness

Experiment 2: effects of frequency

The results of the first experiment showed that the coupling between grip force and load does not adapt when

Table 1 Effects of surface texture on the slope and intercept of the relation between grip and load in experiment 1

Subject	Smooth			Rough		
	Slope	Intercepts	Slip Ratio	Slope	Intercepts	Slip Ratio
A	0.99	12.10–14.58	1.63	0.63	6.96–8.54	0.52
B	0.64	7.76–10.71	0.66	0.50	8.44–9.82	0.54
C	0.50	7.20–10.00	0.69	0.50	3.87–4.72	0.38
D	0.73	11.87–14.63	0.73	0.36	7.26–8.34	0.48

moving at moderate speed. In this experiment, we examined whether this is also the case at higher frequencies. One might imagine that at high frequencies associated with large and rapid changes in load, the CNS might be less inclined to fully modulate grip with fluctuations in load. We asked subjects to make vertical cyclic movements at one of three frequencies: "slower", "faster" and "very fast". At a given rate, the frequencies observed for all four subjects were very similar. The mean frequencies (across trials and subjects) at the slower, faster and very fast rates were 1.43, 2.14 and 3.13 Hz, respectively.

In Figure 4, records from single slower (top), faster (middle) and very fast (bottom panel) trials are shown for subject C. Four waveforms are shown for each trial. Grip force (thick trace), absolute load force (thin trace) and acceleration (dashed trace) are shown in the upper panel of each trial and the force ratio (up to the value of 3) is shown in the lower panel. The dashed horizontal line in the lower panel represents the minimum force ratio observed in the trial. Note that each trial is plotted on a different time scale. The amplitude of acceleration increases markedly with cycle frequency. As a result, the peaks in absolute load force (associated with both the acceleration maxima and minima) also increase with cycle frequency. In all cases, grip force is modulated in parallel with load force. Note that in the slower trial there is only one clear load force peak per cycle, whereas in the faster and very fast trials there are two. (At the two faster rates, the downward acceleration dropped well below $-g$, so that subjects exerted a downward load on the object). Similarly, there is only one grip force peak per cycle in the slower trial and two per cycle in the faster and very fast trials. Moreover, in faster and very fast trials, the smaller and larger grip force peaks seen in each cycle coincide with the smaller and larger absolute load force peaks. Both the mean grip force and the amplitude of grip force modulation increase with frequency. In general, we observed that the minimum force ratio increased with frequency, as is the case in the records shown in Fig. 4.

The minimum force ratio in each cycle was remarkably consistent across cycles, as illustrated in Fig. 4. A similar pattern was observed for the three frequencies and for all four subjects. This indicates that the coupling between grip force and load force was stable throughout the movement regardless of frequency.

Figure 5 shows plots of grip versus load force for two subjects, B (top panel) and C (bottom panel). In each plot, data from a slower trial (solid trace), a faster trial (dashed trace) and a very fast trial (solid trace at top) are shown. The straight dashed line in each plot represents the slip force. In general, the relation between grip force and both positive and negative values of load was well fit by a straight line. (However, in the very fast trial shown for B, the relation between grip and positive values of load is slightly curved. This is one of the very few cases in which the grip-load relation departed from linearity.) The mean grip force increases markedly with cycle frequency. In contrast, the slope of the relation between grip force and load tends to decrease slightly as frequen-

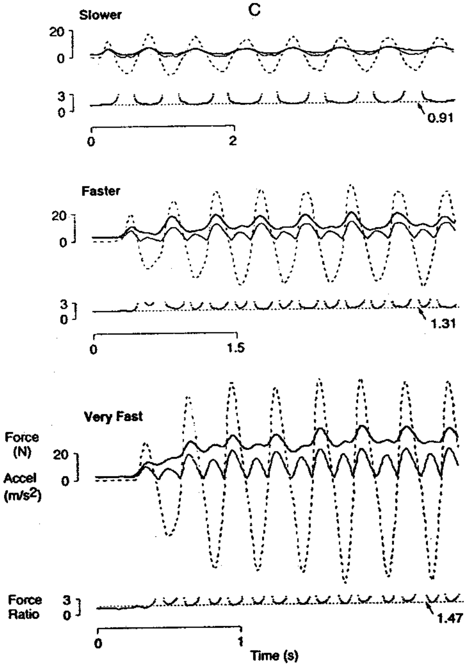

Fig. 4 Single trials from subject C for each cycle frequency (experiment 2). The *top panel* of each trial shows grip force (*thick solid trace*), absolute load force (*thin solid trace*) and acceleration (*dashed trace*). The force ratio is plotted in the *bottom panel* of each trial. The *dashed horizontal line* represents the minimum force ratio observed during the trial

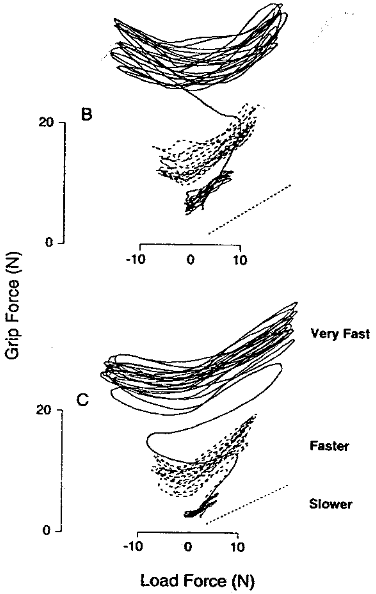

Fig. 5 Plots of grip force versus load force for two subjects in experiment 2: B (*top*) and C (*bottom*). Three trials are shown in each plot: a slower (*solid trace*), a faster (*dashed trace*) and a very fast (also a *solid trace*) trial. The *dashed straight line* in each plot is the slip force

cy increases. (Overall, the slopes tend to be just a little greater than the slip ratio.) Thus, the increase in mean grip force with frequency was achieved primarily by increasing the intercept of the grip-load function.

Linear regression analysis was used to assess the effect of frequency on the slope of the relation between grip and positive values of load. Separate analyses were carried out for each subject. A single slope was estimated for each frequency, while allowing for different intercepts for each of the nine trials (three per frequency). Table 2 presents the slope and range of intercepts for each frequency. For all of the subjects, the intercepts of the faster trials were greater than any of the intercepts of the slower trials, and the intercepts of the very fast trials were greater than any of the intercepts of the faster trials. Thus, without exception, the intercept increased with frequency. In general, the slope of the relation between grip and load decreased with frequency. For all subjects, the slope of the very fast trial was less than the slope of the faster trials ($P<0.001$) and, in three of the four subjects (A, B, D), the slope of the faster trials was significantly less than the slope in the slower trials ($P<0.005$). There was a single exception to this general pattern: for C, the slope of the faster trials was reliably greater than the slope of the slower trials.

Experiment 3: effects of intentional increases in baseline grip force

Here we consider the effect of voluntary increases in the mean force level on the slope of the grip-load function. Subjects first performed three trials at a moderate rate and with normal (self-selected) grip force. They then performed three trials in which they were instructed to increase their grip force to about 25 N before moving and to maintain this heightened grip force during the movement. This represents a substantial increase in mean grip force over the mean grip force values normally observed (10–15 N). Indeed, the baseline grip force was greater than the maximum values usually observed under similar loads. Thus, in principle, modulations of grip force with load would not be required to maintain stability. The subjects then performed three more trials using an even higher grip force (about 35 N). Note that the subjects were not explicitly instructed to keep grip constant during the movement. In this experiment the contact surface was aluminium. This had a coefficient of friction intermediate to those observed for sandpaper and satin.

Figure 6 shows plots of grip force against load for cyclic movements made with and without elevated baseline grip force. Two trials from a single subject are shown in each of the three panels. The upper trace in each panel represents a trial in which the subject was asked to elevate their grip force by 10–15 N. The thick straight lines running through each trace represent the grip force predicted from positive values of load using linear regression. The single dashed lines represent the slip force. For all subjects, the instruction to increase baseline grip force led to an increase in the intercept and a decrease in the slope of the grip-load relation. The mean grip force

Table 2 Effects of cycle frequency on the slope and intercept of the relation between grip and load in experiment 2

Subject	Slower		Faster		Very fast	
	Slope	Intercepts	Slope	Intercepts	Slope	Intercepts
A	1.00	9.75–11.39	0.77	16.08–20.79	0.27	25.82–30.37
B	0.68	6.32–6.59	0.64	9.55–12.06	0.45	25.19–29.54
C	0.54	2.27–2.57	0.78	7.95–9.34	0.51	20.37–24.09
D	0.75	4.30–5.35	0.36	15.29–15.70	0.11	34.37–41.35

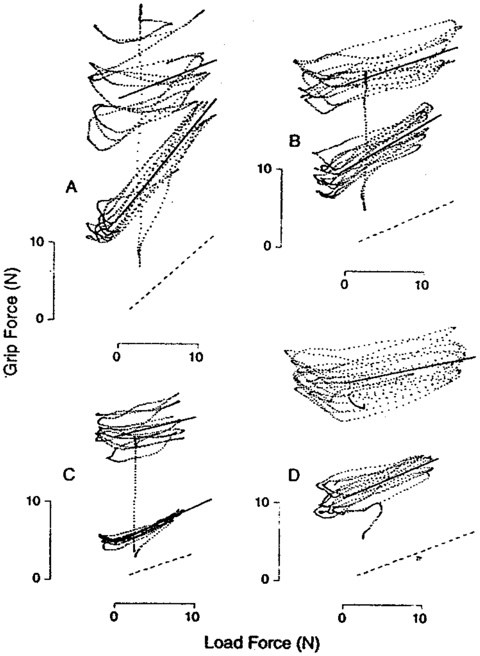

Fig. 6 Plots of grip force versus load for each subject (experiment 3). Two trials are shown in each plot. The *upper trace* shows a trial in which the subject was instructed to elevate their grip force during the trial; the *lower trace* represents a normal trial. The *thick solid lines* represent grip force predicted from positive load force using linear regression and the *thin dashed line* is the slip force

in this case was well above the mean observed under normal conditions. Linear regression analysis was performed on each of the six elevated grip force trials performed by each subject. In all cases, positive and statistically reliable (i.e. non-zero) slopes were observed ($P \leq 0.002$). Thus, grip force increased with load even though the baseline grip force was greater than the maximum grip force that would normally be expected.

In the examples shown in Fig. 6, the slope of the relation between grip force and positive values of load force, although reliably greater than zero, was less when grip force was elevated. In order to quantify the relation between the slope and the level of grip force, we computed the slopes and intercepts for the first five cycles of each of the 9 trials collected per subject (three normal trials and six elevated grip force trials). This yielded 45 observations per subject. Figure 7 shows plots of grip-load slope versus grip force intercept for each subject. The best-fit linear regression lines are shown in each plot analysis. For all subjects, a statistically significant relation between slope and intercept was found ($P<0.001$ in all cases). The greater the grip force intercept, the smaller the slope. (Note that negative slopes were observed in a few cycles).

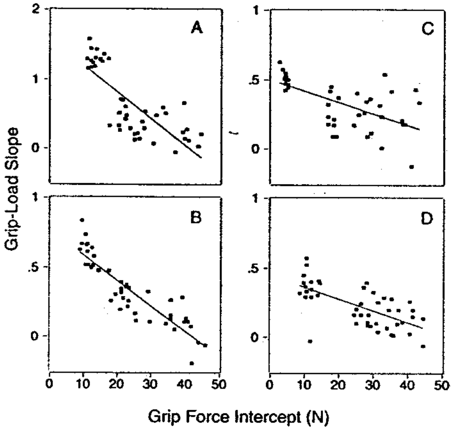

Fig. 7 Plots of the slopes of the grip-load function versus the intercept for each subject (experiment 3). Slopes and intercepts were computed for five cycles within each of the nine trials with varying grip force levels. In all subjects, the slope of the grip-load function varied inversely with the grip intercept. Thus, the greater the grip force, the less the grip-load modulation

In summary, the results of the third experiment show that, when subjects were instructed to maintain an elevated grip force, well above normally observed levels, the slope of the relation between grip and load decreased. However, the coupling was not abolished and grip force still varied directly with load force.

Discussion

We have examined cyclic arm movements in which the load acting on a hand-held object fluctuated with object acceleration. We have shown that grip force was modulated in parallel with load regardless of movement frequency and the texture of the gripping surface; grip force increased and decreased as the load force rose and fell. The modulation of grip force with load continued across repeated cycles of movement. Moreover, the extent of modulation for a given change in load appeared to be approximately constant throughout. Neither the slope of the relation between grip force and load nor the values of the minimum force ratio varied systematically across movement cycles. These findings support and extend our earlier results (Flanagan and Tresilian 1994; Flanagan et al. 1993).

In the first experiment, the texture of the contact surface, and hence the friction between the skin and the object, was varied. We found that both the overall level of grip force (offset) and the extent of grip force modulation with load (gain) increased with surface slipperiness. In other words, both the slope and the intercept of the relation between grip and load increased with slipperiness. Previously, Johansson and Westling (1984) have shown that the slope of the relation between grip and load in lifting increases with surface slipperiness and that the grip force developed just prior to pulling up is greater. Our results demonstrate that a similar pattern holds for loads induced by predictable movement kinematics.

In the second experiment, the cycle frequency was varied. Increases in frequency were associated with increases in both the extent of load modulation and the rate of change of load. We found that, as frequency increased, the overall level of grip force increased. However, in general, the extent of grip force modulation with load (i.e. the gain of the relation between grip and load) decreased. Thus, when taking into account changes in both texture and frequency, we find a dissociation between the grip force offset and the grip force gain with respect to load. In other words, it appears that the grip force gain and offset can be varied independently across conditions. This suggests that these parameters are under the influence of high-level motor commands.

It is interesting to speculate on the possibility of centrally mediated gating of cutaneous afferent information during movement akin to the suppression of visual information which occurs during saccadic eye movements (e.g. Bridgeman et al. 1979; Volkmann 1986). Chapman and colleagues (see Chapman 1994 for a review) have provided evidence of cortical gating of somatosensory signals in active touch where the fingertips are actively moved across a textured surface. These mechanisms might also operate during rapid arm movements with a hand-held load. During rapid arm movements there may be an increased number of "microslips" between the skin and object, due to loading. Thus, it may be desirable to attenuate cutaneous afferent inputs so that the CNS only responds to large and functionally significant slips. It may be that the reduced grip force modulation observed at higher movement frequencies results in decreased sensory feedback. On the other hand, the reduction of modulation may reflect an adaptation in order to maintain a higher safety margin in the face of reduced sensitivity.

In the third experiment, we instructed subjects to maintain an elevated grip force throughout the movement. We found that grip force was still modulated in parallel with load, even though grip force was well above the normal level and modulations were not necessary to prevent slip. However, the extent of grip force modulation with load was greatly reduced. In a task in which subjects resisted unpredictable pull forces, Cole and Johansson (1993) examined the relation between the grip force prior to the pull and the size of the catch-up response immediately following the pull, whereby grip force was rapidly increased so as to achieve the desired ratio of grip force to load force. These authors showed that when subjects were instructed to use a greater initial grip force, the catch-up response was smaller. However, the reduction of catch-up response did not fully compensate for the increased initial grip force, and, as a result, the grip at the end of the catch-up phase was larger than needed. This suggests that there is a low-level mechanism not fully tuned to high-level voluntary adjustments of grip force. This is consistent with our results. The apparently obligatory coupling suggests that the coupling between grip force and load does not result simply from a high-level mechanism generating grip force on the basis of predicted load and surface slipperiness. The results are also consistent with qualitative observations we made in a previous paper (Flanagan et al. 1993), in which we noted that when subjects were asked to keep grip force constant during a cyclic movement, they failed to do so and grip force continued to modulate in phase with load. However, we observed that some subjects were able to limit the extent of modulation by increasing their grip force.

Although there appears to be an obligatory coupling between grip force and load force when simply moving a hand-held object, this coordination is by no means fixed. Johansson and Westling (1988b) have reported that if subjects view a ball dropped into a cup they are holding, there is an anticipatory increase in grip force just prior to contact. We have examined a similar task involving cyclic arm movement. Subjects were required to repeatedly bounce a tennis ball on a small platform mounted on top of a force transducer held with a precision grip. A brief increase in grip force was observed just prior to each ball contact even though the load force at the time of contact was typically decreasing (unpublished data). Thus, the normal coupling between grip and load, which was seen when the ball was in the air, was disrupted just prior to ball contact. It may be that the anticipatory increase in grip force observed just prior to ball contact was superimposed on the anticipatory fluctuations in grip force associated with movement-related loads (see Wing 1995).

It is interesting to compare the coordination of grip force and movement-induced load observed when transporting a hand-held object with the coordination of hand aperture and hand transport when reaching to grasp an object. In reaching to grasp, hand aperture is temporally linked to hand transport (e.g. Jeannerod 1981; Wallace and Weeks 1988; Wing et al. 1986). However, although the coupling between hand aperture and hand transport can be voluntarily abolished, the coordination of grip force and movement-induced load force appears to be difficult to suppress. This suggests a different balance between high-level (modifiable) and low-level (inflexible) control mechanisms in the two tasks. This may reflect differences in the sensorimotor mechanisms involved. In normal reaching, visual information about the location and size of the object is used to calibrate the transport and grasp components, whereas, when moving a hand-held object, cutaneous and kinesthetic information is used to parameterize the movement.

A recent focus of research in the area of motion planning and control has been on the identification of movement cost functions (e.g. Cruse et al. 1990; Flash and Hogan 1985; Hogan 1984; Nelson 1983; Rosenbaum et al. 1993; Uno et al. 1989). Although a range of costs has been proposed, many are related to efficiency of movement defined either in terms of motion kinematics (e.g. Flash and Hogan 1985) or dynamics (e.g. Uno et al. 1989). In the context of precision grip force control, Johansson and Westling (1984) have suggested that grip force changes in parallel with load force in order to economise muscular effort. The idea is that by changing grip force in parallel with load, the grip force will never be greater than is necessary to maintain a minimum safety margin. However, in movements with rapid and large fluctuations in load, there may also be a cost associated with rapid and large changes in grip force. For example, antagonist activity may be required to decrease the grip force. Thus, it may be more efficient to reduce the extent and/or rate of grip force modulation by increasing the overall level of grip force. This strategy might be employed during higher frequency movements in which we observe a decrease in the gain of the grip-load relation and an increase in the overall level of grip force. The idea that the CNS uses more then a single cost function in performing tasks has recently been promoted by Rosenbaum et al. (1993). Indeed, these authors suggest that the CNS is able to weight different costs depending on the demands of the task. For example, in their model of reaching, there are two costs (one related to a spatial accuracy and another related to joint displacement) which can be differentially weighted depending on task demands.

The finding that the coupling between grip force and load persists and is stable in extended cyclic movements means that the grip force may be used as an effective index of motion planning under these conditions. In the cyclic movements we have examined, the fluctuations in load are highly predictable; they depend only on the mass of the object, which was constant, and the object's acceleration. However, in other tasks the mapping between load and movement kinematics may be more complex (e.g. the load may act as a damping mass-spring). Our findings suggest that grip force might be used to assess the extent to which such loads can be predicted in movements over an extended period of time. Thus, grip force could be exploited to provide a window into motion planning. By monitoring grip force during movements with different loads, it may be possible to assess the sensitivity of anticipatory planning to various load conditions other than the inertial loads we have examined here.

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