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Grip–Load Force Coupling: A General Control Strategy for Transporting Objects

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The authors examined the coupling of grip force and load force during point-to-point and cyclic arm movements while holding an object in a variety of grips, including 1- and 2-handed grips and "inverted" grips. In all grips, grip force is modulated in phase with fluctuations in load force that are induced by the arm movement. The tight temporal coupling between grip force and load force seen when moving an object held in a precision grip (J. R. Flanagan, J. Tresilian, & A. M. Wing, 1993) is observed in other grips. The control of precision grip force during whole-body jumping movements was also investigated. Grip force was modulated in phase with changes in load force induced by jumping even though the arm's joint angles were fixed. The tight temporal coupling between grip force and load force during object transport reflects a general control strategy that is not specific to any particular grip or mode of transport. Models of the coordination of grasp and transport in prehensile behaviors are discussed.

There are two aspects to the coordination between grip and transport components of prehensile behaviors: (a) coordination of anticipatory grip aperture formation with arm transport movements during reaching for a stationary object, and (b) coordination between grip force and transport movements when holding an object. The first aspect has been widely studied (e.g., Arbib, 1981; Haggard & Wing, 1991; Jeannerod, 1981, 1984; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990; Wallace & Weeks, 1988; Wing, Turton, & Fraser, 1986), and the anticipatory aperture formation component has been found to be tightly temporally coordinated with the transport movements. The second aspect has been less well studied. Johansson and Westling (1984) have documented anticipatory changes in grip force prior to lifting objects using a precision grip with the distal pads of the index finger and thumb at the sides of the object (see Figure 1). They have also shown that grip force changes in anticipation of load forces induced by pulling on spring-loaded (Johansson & Westling, 1984) and fixed objects (Johansson, Riso, Hager, & Backstrom, 1992). Johansson and colleagues concluded that although anticipatory changes in grip force are centrally programmed, sensory information is important in the development of these anticipatory changes, especially in achieving fine grip force control. In particular, afferent information from mechanoreceptors in the skin appears to be involved in maintaining a constant ratio of grip force to load force during manipulation (Johansson et al., 1992). Of course, afferent information is also important for mediating reflex responses to unexpected perturbations that might lead to slip (Cole & Abbs, 1988; Johansson & Westling, 1987).

Johansson and colleagues did not document the relation between grip forces and changing load forces during active movement of a held object. We have recently extended the study of grip and transport coordination to this case (Flanagan, Tresilian, & Wing, 1993; Flanagan & Wing, 1993). When an object is held in the hand with a precision grip (i.e., between the tips of the thumb and forefinger) and moved by the arm, grip force is modulated in phase with the object's acceleration (Flanagan et al., 1993). This modulation is anticipatory in the sense that changes in grip force occur at almost exactly the same time as changes in load force induced by the acceleration. Increases in grip force prevent slippage that might otherwise result from the changes in load. What is particularly striking is that grip force not only rises as the load increases but falls as the load decreases. This kind of anticipatory modulation of grip force in phase with changing load force is not the only means for preventing slippage—other methods are possible. For example, the same goal could be achieved by increasing grip force to the expected maximum magnitude prior to moving and then decreasing it again on completion of the movement. Like other motor control tasks, there are different means for achieving the same end. The question arises, therefore, as to whether people can adopt different yet functionally equivalent strategies for preventing slippage of a gripped object.

In this article we consider whether the precise grip force–load force coupling we observed during active transport of an object held in a precision grip reflects a general control strategy. At least two questions can be posed: First, is the precise coupling observed when objects are moved while held in grips other than the precision grip? It is clear that the

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precision grip is particularly well suited to fine force control—it involves small muscles, and the contact surfaces of thumbs and index fingers have dense afferentation (cf. two point thresholds). Thus, when using other grips where larger muscles and less sensitive sensory surfaces may be involved, will load force and grip force show an essentially similar coordination, or is the precision grip in some sense special? Second, does the coupling depend on the articulators used to generate the movement?

To address the first question, we examined a variety of grips that are diagrammed in Figure 1. Both normal and "inverted" grips (referred to in this article as *pirgs*) were used. The pirgs required outward rather than inward force to hold the object, as shown in Figure 1. Thus, as load force increased, the subject needed to push (precision pirg) or pull (thumbs pirg) outwards to prevent the object from slipping.

To address the second question, we recorded grip force and load force as subjects jumped while holding an object. In this case the object was actively moved by the subject, but there was no arm movement. Because the transport movement was in a sense "external" to the arm–hand effector system involved in prehension, it is possible that changes in load force induced by jumping behaved like an externally imposed load change and not like the changes in load induced by active arm movements. On the other hand, the active jumping movement could be coupled directly to the grip force mechanism and so behave equivalently to an arm movement. Johansson et al. (1992) examined grip force responses to experimenter-induced, unpredictable ramp changes in load while subjects hold an object. Grip force began to rise about 70 ms after the onset of a ramp increase in load. This is about the time expected for a supraspinal reflex response (see also Cole & Abbs, 1988; Johansson & Westling, 1987). Initially, grip force rises quickly during a "catch up" phase to establish a safe grip–load force ratio and thereafter increases in parallel with load force so as to keep this ratio approximately constant. If the load force changes on a handheld object induced by jumping behave like an externally imposed load, a mechanism like that documented by Johansson et al. (1992) could be used that would lead to a similar pattern of grip force modulation. In this case we would expect grip force to rise after the onset of the jumping movement in an attempt to maintain a safe grip–load force ratio. Alternatively, if load force changes induced by jumping are dealt with by a mechanism equivalent to that used during active arm movement, we would expect the grip force to modulate with load force in an anticipatory fashion as we have observed during rapid arm movements (Flanagan et al., 1993).

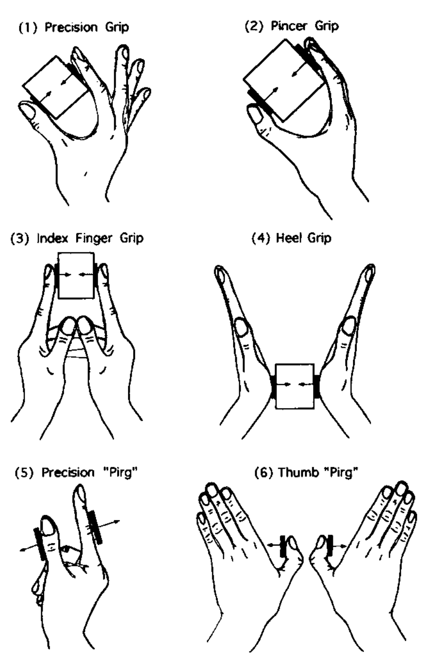

Figure 1. Top view drawings of the six grips examined in this article. Pirg = inverted grip.

Experiment 1

We designed this experiment to investigate the coupling of grip force and load force during point-to-point arm movements with an object held in a variety of grips and point-to-point jumping movements with an object held in a precision grip and with the joint angles of the arm held constant. The direction of movement (up or down) was varied in order to produce different patterns of load force changes during the movement. In this way, we were able to assess the extent to which modulations in grip force in the different grips depended on the pattern of load force fluctuation. By examining jumping movements with the joint angles of the arm fixed, we were able to assess the coupling of grip and load forces in a situation in which fluctuations in load force were induced by voluntary movement (i.e., jumping), but where arm motion was absent.

Method

Subjects. Four adult subjects, 2 of whom were the authors, participated in this study. None reported sensory or motor problems. All subjects gave informed consent before participating. The 4 subjects were right-handed and used their right hands to grasp the object in the one-handed grips (see Figure 1).

Apparatus. Subjects grasped a cylindrical force transducer (Novatech, Model 241) with one of the six grips depicted in Figure 1. A schematic of the transducer, grasped with a precision grip, is shown in Figure 2. An accelerometer (Entran, Model EGB-125-10D) mounted on top of the transducer measured acceleration in the direction of movement. The mass of the transducer was 0.26 kg, and the width between grip surfaces was 58 mm. The object's center of mass was located midway between the contact points of the thumb and index finger. Thus, the load force acted through the center of the object and did not act to rotate the object during steady grasp or during arm movements. The contact surfaces were steel and were fixed to the transducer with a flat-head screw, which was flush with the surface.

Subjects were instructed to move the object in a straight line and to keep the orientation of the object constant. The movements were monitored by the experimenter throughout the experiment to ensure that the subjects complied with these instructions. For one

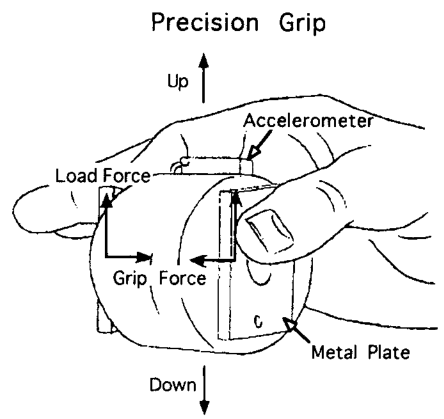

Figure 2. The force transducer held in a precision grip. An accelerometer mounted on top of the transducer recorded acceleration in the vertical.

subject, an electromagnetic sensor (Ascension) was used to monitor the position and orientation of the hand during the experiment. The results showed that this subject was able to produce straight line movement and kept the orientation of the hand and object constant during the movement.

A 16-bit analog-to-digital interface board (National Instruments, Model M10 16X) and a Macintosh IIfx computer were used to collect and store the data. Data collection and analysis were carried out with the LabVIEW graphical programming language (National Instruments).

Experimental procedure. For each grip, subjects produced three upward arm movements followed by three downward arm movements. When subjects completed the six movements for one grip, they then moved to another. The grips were tested in the following order: precision, pincer, index fingers, heels of hands, inverted precision, inverted thumbs. However, movements with the pincer grip were not recorded from the first subject (S.K.). Subjects were given a rest between grips to eliminate any possible effects of fatigue. They were also encouraged to rest whenever they wanted. In the precision grip, the distal pads of the thumb and index finger contacted the sides of the object. The pincer grip was similar to the precision grip except that the pads of all four fingers contacted one side. In the index finger grip, the object was held with the distal pads of the index fingers at the sides. The other fingers of each hand were interleaved and the tips of the thumbs were joined together so as to provide stability. In the heels grip, the object was held between the heels of the hands, with the fingers and thumbs extended. Finally, in the two inverted grips, outward pressure was applied to the contact surfaces. In other words, friction between the object and the digits was increased by making the grip force increasingly negative. Thus, we would expect an inverse relation between grip force and load force. In the precision pirg, the dorsal sides of the thumb and index finger pressed out against the contact surfaces. In the thumbs pirg, the distal pads of the thumbs pulled out against the contact surfaces. For the inverted grips, longer contact plates, extending above the transducer, were used so that the digits could be placed on the inside surfaces.

Subjects were instructed to move at a moderate rate and to produce fairly large amplitude movements. The amplitude ranged between 30 and 40 cm. However, targets were not supplied and there were no explicit accuracy requirements. Grip and load force were also recorded during "point-to-point" jumps in 2 subjects (the authors). The subjects jumped up from the floor to a surface 44 cm above the ground and then down again. In both the upward and downward jumps, the subjects jumped forward about 20 cm. The data presented for the point-to-point jumps are from first trials.

Data analysis. Onsets and peaks were determined from grip force and acceleration records after smoothing with a digital low-pass filter (Butterworth, 4th order, zero phase lag), with a cutoff frequency of 12 Hz. The onset was taken as the point at which the value exceeded the mean $\pm$ 2 standard deviations of the premovement resting value.

Load force was calculated as the absolute value of the product of the object's acceleration and mass, where the acceleration was the sum of the acceleration of the movement and the acceleration due to gravity. In other words, the load force was defined as the magnitude of the resultant of the inertial and gravitational forces acting on the object.

Results and Discussion

The results include individual records as well as summary statistics. The records were selected to be representative of all subjects and trials. It should be noted that a very similar pattern of results was observed across all trials and subjects. All of the figures show results from 2 subjects. Data from 1 subject (R.F.) are presented in all of the figures so that direct comparisons can be made across tasks. Three figures present the results for movements with the one-handed (precision and pincer), two-handed (index finger and heels), and inverted grips (precision and thumbs pirgs). The emphasis is on the qualitative relation between grip force and load force rather than on quantitative detail.

One-handed grips. Figure 3 shows grip force (thick lines), acceleration (thin lines), and load force (dashed lines) records for upward and downward arm movements. The same line types are used in all figures. Upward and downward arrows indicate the direction of movement. The object was held with either a precision (top four panels) or a pincer (bottom four panels) grip. Records from subjects A.W. (left) and R.F. (right) are presented. Note that before and after the movements, the load force was purely gravitational and, thus, equal to the weight of the object. However, during the movements, load force fluctuated as a result of inertial forces proportional to object acceleration. Load force was maximal at the point of maximum acceleration where gravitational and inertial forces acted in the same direction. The acceleration maximum occurred near the start of upward movements and close to the end of downward movements. Load force at the time of minimum acceleration was smaller than at the time of maximum acceleration because gravitational and inertial force acted in opposite directions and tended to cancel each other out. However, when the object was decelerated rapidly, such that the acceleration was well below $-g$ (the acceleration due to gravity), then another load force peak was observed.

The acceleration and load force profiles shown in Figure 3 are qualitatively similar across grips. Thus, it is reasonable to compare the precision and pincer grip force profiles. Although the 2 subjects exhibited slightly different patterns of grip force modulation, the patterns of precision and pincer grip modulation were similar. Consider first the upward movements. As we have reported previously for the

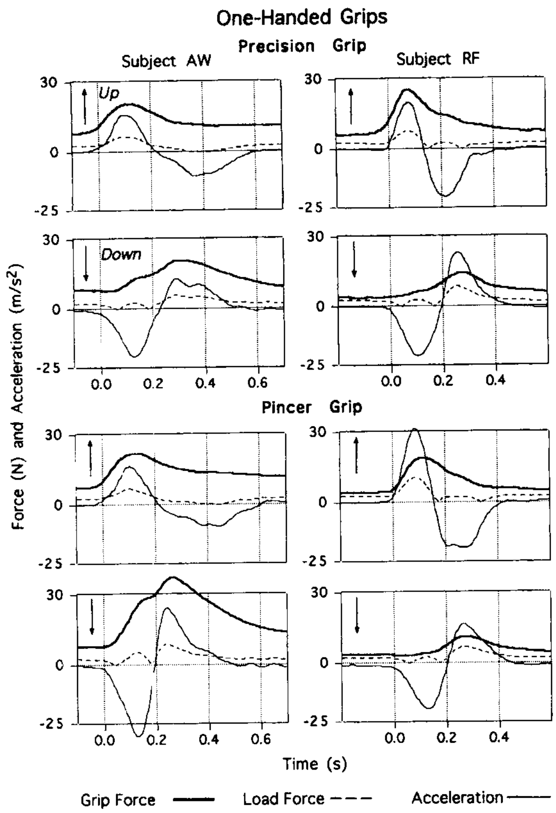

Figure 3. Individual records for subjects A.W. and R.F. from upward and downward point-to-point movements made while holding the object in a precision or pincer grip. Each panel shows grip force, load force, and acceleration. Arrows indicate the direction of movement.

precision grip (Flanagan et al., 1993), grip force begins to increase just before load force increases (see Table 1) and then rises in parallel with load force up to a maximum, which occurred just after the load force maximum. On average, maximum load force preceded maximum grip force by 25 ms (precision grip) and 31 ms (pincer grip) in upward movements (Table 2). When data from all trials and subjects were lumped together, strong positive correlations ($r > .99$, $p < .01$) between the time to maximum grip force and time to maximum load force were found for both grips. Thus, not only did the grip and load force maxima occur at about the same time, they were also highly correlated on a trial-by-trial basis. After the maximum, grip force decreased for the remainder of the movement, and as we have reported before (Flanagan & Wing, 1993), the grip force at the end of the movement was often greater than the steady level before the movement. At the time of minimum acceleration, near the end of the upward movements, A.W.'s load force was close to zero. In contrast, a second load force peak was seen for R.F. because this subject decelerated more rapidly. Associated with R.F.'s second load force peak was a "bulge" or inflection in grip force, which was not present in A.W.'s records. A similar bulge was observed in both the precision and pincer grips for R.F. The bulge—a reduction in the rate of grip force fall—may guard against slippage that might otherwise result from the rise in load force. Thus, although the 2 subjects produced somewhat different grip force patterns, this can be attributed, at least in part, to differences in load force modulation.

Consider now the downward movements. Again, there were slight differences among subjects; however, each produced similar patterns of grip and load force variation for the precision and pincer grips. Maximum load force occurred near the end of these movements as the downward motion of the object was slowed down. However, as in the upward movements, the load and grip force maxima coincided closely in time though generally in the reverse order with maximum grip force occurring just before maximum load force (see Table 2). As in the upward movements, correlations between maxima times were strong and positive ($r > .96$, $p < .01$) for both grips.

In downward movements, grip force typically did not begin to increase until after the start of the movement. However, an increase in grip force was observed shortly after the start in the trials where the downward acceleration decreased well below $-g$, thereby producing an increase in load force (see, in particular, A.W.'s records). Note that although A.W.'s maximum grip force was far greater with the pincer grip than with the precision grip, so was the maximum load force (Figure 3). Thus, the heightened grip force may have served to guard against slippage. Although subjects were always told to move at a moderate rate, in all 3 subjects tested on the pincer grip, maximum acceleration was, on average, higher with this grip than with any other (see Table 3).

In summary, all of the movements shown in Figure 3 reveal a striking correspondence between grip force and load force. The maximum grip force always coincides with the maximum load force and, where smaller peaks in load occur, there is inevitably an increase or at least a "bulge" in grip force. In upward and downward movements, grip force is modulated in phase with load force, regardless of whether the object is held in a precision or a pincer grip.

Two-handed grips. Figure 4 shows grip force, load force, and acceleration records for upward and downward

Table 1
Time (in Milliseconds) From the Onset of Grip Force Rise to the Onset of the Increase in Load Force at the Start of Upward Point-to-Point Movements

	Time from grip force onset		
Grip	*M*	*SD*	N
Precision	46	35	12
Pincer	25	16	9
Index fingers	20	25	12
Heels	13	26	12
Precision pirg	55	84	12
Thumbs pirg	20	23	12

Note. In all cases, grip force starts to rise before load force begins to increase. The standard deviation in the precision pirg is more than twice the standard deviations in the other grips. Pirg = inverted grip.

Table 2
Time (in Milliseconds) From Peak Grip Force to Maximum Load Force in Point-to-Point Arm Movements

	Time from peak grip force					
	Up			Down		
Grip	*M*	*SD*	N	*M*	*SD*	N
Precision	−31	22	12	20	33	12
Pincer	−25	35	9	−4	27	9
Index fingers	−88	30	12	7	45	11
Heels	15	32	12	27	29	12
Precision pirg	−90	60	11	35	108	12
Thumbs pirg	−80	48	12	29	46	11

Note. Means and standard deviations of upward and downward movements were computed from all trials and subjects for each grip. Peak grip force tended to occur just after maximum load force in upward movements and just before maximum load force in downward movements. Pirg = inverted grip.

arm movements made while holding the object with one or the other of the two-handed grips. The top four panels show movements with the "index finger" grip and the bottom four panels show movements with the "heels" grip. Individual trials recorded from subjects J.T. (left) and R.F. (right) are shown. As was the case for the one-handed grips, grip force was modulated during the movement, and the pattern of modulation was sensitive to the load force profile. The grip force and load force maxima occurred at about the same time with the exception of the upward movements with the index finger grip, where the average lag between maximum load force and maximum grip force was 90 ms, some 60 ms greater than the lags observed for the one-handed grips (Table 2). However, with each grip, strong positive correlations ($r > .93$, $p < .001$) were observed for both upward and downward movements. Note, also, that the *SD*s of both T1 (the time from grip force onset to load force onset) and T2 (time from maximum grip force to maximum load force) in the one- and two-handed grips were comparable (Tables 1 and 2).

In trials where the load force was close to zero at the time of minimum acceleration, the grip force was near or below the premovement level (see J.T.'s movements with the "heels" grip in Figure 4). In contrast, in trials where a clear (secondary) peak in load force was observed at the time of minimum acceleration, grip force was elevated well above the premovement level. Indeed, as with the one-handed grips, a bulge or even a local peak in grip force often coincided with the load force peak. Thus, even some of the more subtle aspects of the coordination between grip force and load force observed with the precision and pincer grips were preserved in the two-handed grips.

Repeated measures analysis of variance (ANOVA) was used to test for differences in mean values of T1 and T2 between the one- and two-handed grips. A significant difference was observed only for T2 in upward movements, $F(1, 2) = 21.8$, $p < .05$. Although there may be quantitative differences between the one- and two-handed grips, the basic pattern of grip force modulation is similar. In both cases, grip force tended to rise as load force increased and fall as load force decreased.

Inverted grips. In Figure 5, grip force, load force, and acceleration records are shown for the precision pirg (top panels) and the thumbs pirg (bottom panels). Individual trials from upward and downward arm movements are shown for subjects A.W. and R.F. As can be seen, grip force was clearly modulated during the movements with the inverted grips. However, the coupling between grip force and load force was weaker, especially in the precision pirg, than in the other grips. As with the other grips, changes in grip force preceded changes in load force in the upward movements. However, the *SD* of T1 was more than twice as great in the precision pirg (84 ms) than in other grips (≤35 ms). Similarly, the *SD*s of T2 in both the upward and downward movements were about twice as great in the precision pirg than in the others (see Table 2). Finally, the correlations between time to maximum load force and time to peak grip force in the upward movements were weaker in the two inverted grips ($r = .88$ in both) than in any of the other grips

Table 3
Means and Standard Deviations (in Milliseconds), for Each Grip and Subject, of Maximum Acceleration in Point-to-Point Arm Movements

	Maximum acceleration (m/s^2)							
	A.W.		J.T.		R.F.		S.K.	
Grip	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Precision	14.6	4.4	16.6	1.6	19.1	4.5	15.0	2.9
Pincer	22.3	4.9	22.9	5.3	21.6	9.8	NA	NA
Index fingers	16.2	3.3	15.7	4.1	16.4	1.5	11.7	1.8
Heels	12.2	6.4	12.7	2.4	15.6	3.3	8.5	1.4
Precision pirg	9.2	2.2	9.9	1.6	9.0	1.8	10.0	1.1
Thumbs pirg	14.5	2.9	16.3	4.1	18.5	4.4	12.7	3.0

Note. Note that maximum acceleration was smallest for the precision pirg in all subjects except S.K., where it was second smallest. Maximum acceleration was largest for the pincer grip in all 3 subjects who performed this grip. (S.K. did not perform the pincer grip.) Pirg = inverted grip; NA = not applicable.

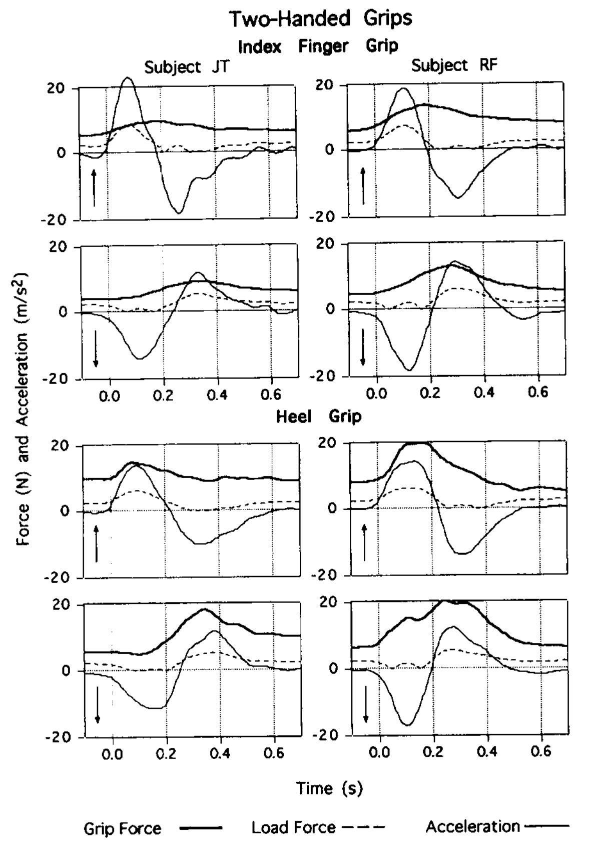

Figure 4. Individual grip force, load force, and acceleration records for subjects J.T. and R.F. from upward and downward point-to-point arm movements made with the object held between the index fingers or heels of the hands.

($r \geq .95$ in all cases). In the downward movements, the correlations were clearly less only in the precision pirg ($r = .74$) as compared to the other grips ($r \geq .96$ in all cases).

In the precision pirg, the dorsal surfaces of the digits contact the object rather than the distal pads or pulps. Presumably, the sensory information provided in this case is degraded in comparison to the standard precision grip. This may explain, at least in part, the higher variability observed in the precision pirg. (Note that the variability observed in the thumbs pirg, where the pulps contact the object, is less than in the precision pirg.) Alternatively, the increased variability in the precision pirg may reflect mechanical properties of the contact surface. Because the pads of the digits are more compliant than the dorsal surfaces of the digits, the tolerance for low amplitude fluctuations in grip may be greater in the standard precision grip than in the precision pirg. Thus, the increased variability in the latter might reflect the need for more high-frequency adjustments in grip to compensate for the lack of tolerance.

As shown in Table 3, maximum acceleration was, on average, smaller in the precision pirg than in any other grip. Although this could be interpreted as support for the notion that this grip is a less stable grip than the others, it might simply reflect the fact that only relatively small grip forces can be generated with this grip and so, therefore, only smaller inertial loads can be tolerated.

Although the coupling of grip force and load force appears to be somewhat weaker in the precision pirg, it is nevertheless the case that grip force was modulated during the movement and that the pattern of modulation depended on the timing of load force fluctuations. In particular, in both inverted grips, peak grip force occurred relatively early in the upward movement and relatively late in the downward movement. Thus, grip force is temporally linked with load force so as to guard against slippage.

The finding that grip force modulates with load force during movement with an inverted precision grip suggests the coupling between grip and load force observed across grips is neurally based and is not simply due to the mechanical actions of muscles, because very different muscles are involved in producing grip force in the various grips. The main argument against this idea that the coupling is mechanical in nature is that there is no increase in grip force until about 70 ms after an unexpected perturbation that loads the object (Cole & Abbs, 1988; Flanagan et al., 1993; Johansson & Westling, 1984). If grip force increased as a

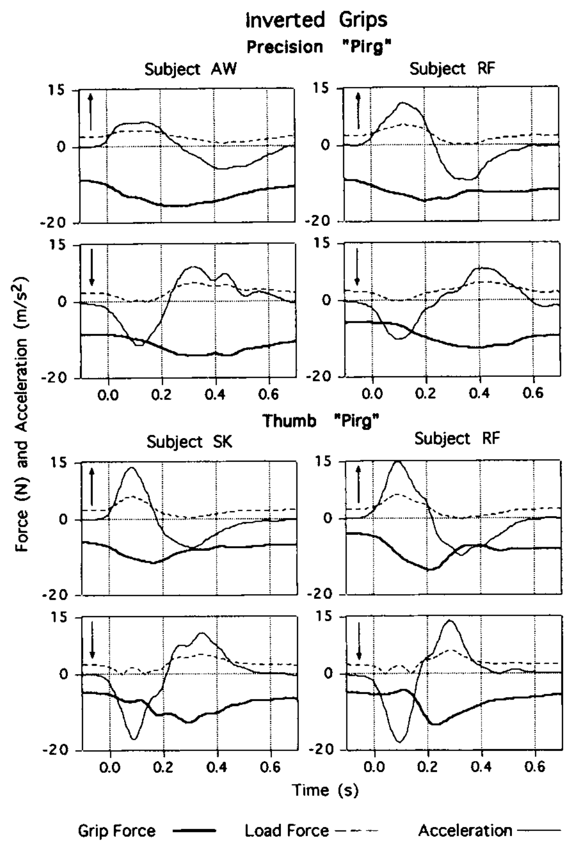

Figure 5. Grip force, load force, and acceleration traces from single upward and downward point-to-point arm movements made while subjects A.W. and R.F. held an object in a precision or thumb pirg (inverted grip).

mechanical consequence of loading, then grip force would have been expected to increase immediately after the perturbation.

Comparison of grips. In all of the grips we examined, grip force was modulated during the movement, and the pattern of modulation was sensitive to fluctuations in load force. In general, grip force varied in phase with load force; the absolute grip force rose and fell as load force increased and decreased. In both upward and downward movements, peak grip force tended to coincide closely in time with maximum load force. With three exceptions, peak grip force occurred, on average, within 35 ms of maximum acceleration. Larger time intervals between maximum load force and peak grip force (T2 ≤ -80 ms) were observed with the precision pirg and in upward movements with the heels grip and thumbs pirg. Furthermore, in all of the grips, grip force began to increase prior to load force in the upward movements. The average lags between the onset of grip force rise and the onset of load force rise (T1) ranged from 13 to 55 ms.

To compare the different grips in terms of their efficiency, we computed the ratio of maximum absolute grip force to maximum load force (GL_{max}). The smaller the grip force used to hold a given load, the more efficient the grip. Johansson and Westling (1984) have shown that the ratio of grip force to load force does not vary appreciably with load when lifting objects with a precision grip. Thus, GL_{max} provides an index of grip efficiency that is load independent. This enables us to compare grips even though the maximum load forces, observed during movement, may have differed.

The means and *SD*s of GL_{max} for the six grips are presented in Table 4. The means are based on both upward and downward movements from all of the subjects. As can be seen, GL_{max} was smallest in the index finger grip and largest in the heels grip and precision pirg. A similar pattern of results was seen for each subject. In 3 of the 4 subjects, GL_{max} was smallest in the index finger grip. Likewise, the heels grip and precision pirg exhibited the two largest values of GL_{max} 3 of the subjects. Planned contrasts with one-way ANOVAs (overall $F[5, 129] = 6.01, p < 0.001$) were carried out to test (a) whether GL_{max} was significantly smaller in the index finger grip than in the precision, pincer, and inverted thumb grips combined, and (b) whether GL_{max} in the heels and inverted precision grips were significantly larger than in the precision, pincer, and inverted thumb grips combined. The data from the different subjects were lumped together. Both the first ($t[23] = 2.5, p < .05$) and the second ($t[23] = -3.75, p < .01$) tests proved significant.

In summary, we conclude that the coupling between grip force and load force during arm movements is not restricted to precision grip but is also observed in the pincer grip, two-handed grips (including a grip where the fingers are not involved), and inverted grips where outward pressure is required to keep the object from slipping.

Point-to-point jumping movements. The control of grip force was also examined in jumping where movement-induced fluctuations in load force were observed in the absence of arm movement. Grip force (thick traces) and load force (dashed traces) records from first trial upward and downward jumps are shown in Figure 6. As might be expected, in the upward jumps peak load force was greater at take-off than at landing whereas, in the downward jumps, the load force at landing was greater than at take-off. The same pattern was observed in terms of the grip force, which was modulated almost perfectly with the load force. Indeed, the correspondence between grip force and load force was remarkable, especially given the fact that the load resulted from forces generated and absorbed by the whole body. Note that the load force peaks were well separated in time and the load force, between peaks, remained below the resting (i.e., premovement) level for about 200 ms. However, with the exception of R.F.'s downward jump, the grip force tended to remain elevated above its resting level. T1 values, which were obtained for both upward and downward jumps, ranged between 20 and 66 ms and T2 values ranged between -47 and 88 ms. Thus, grip force starts to increase just prior to the load force and the absolute lag between the grip and load maxima is quite small.

The finding that grip force is modulated in phase with load force during jumping movements indicates that anticipatory changes in grip force parallel movement-induced fluctuation in load force independently of the mode of transport. In other words, grip force rises as load force increases and falls as load force decreases regardless of whether the change in load force is produced by movement of the arm or movement of the body (as in the case of jumping). Thus, the coordination of grip force and load force is not restricted to hand and arm but encompasses the whole body. In the next experiment, we examined the stability of these different grips during cyclic arm movements and jumping movements.

Table 4
Ratio of Maximum Absolute Grip Force (G_{max}) to Maximum Load Force (L_{max})

	$\|G\|_{max}:L_{max}$		
Grip	*M*	*SD*	N
Precision	3.71	1.28	24
Pincer	3.51	1.33	18
Index fingers	3.00	0.79	23
Heels	6.76	5.49	24
Precision pirg	5.04	1.72	23
Thumbs pirg	3.85	2.21	23

Note. Pirg = inverted grip.

Experiment 2

We designed this experiment to investigate the coordination of grip force and load force during cyclic arm movements with the object held in various grips and repetitive up and down jumping movements with the object held in a precision grip. By examining cyclic movements, the stability of the grip–load coupling over time can be assessed. In a previous report (Flanagan et al., 1993), we demonstrated

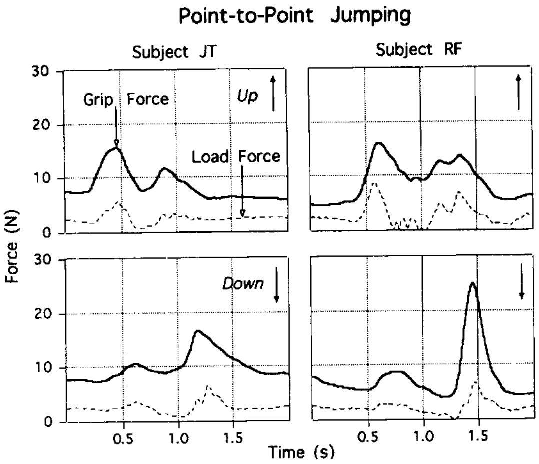

Figure 6. Individual grip force and load force traces from point-to-point upward and downward jumps with the object held in a precision grip. The data are from first trials for subjects J.T. and R.F.

that when moving an object held in a precision grip with the arm, grip force is modulated in phase with the load force. Thus, the coupling observed in point-to-point arm movements is preserved in cyclic arm movements. Experiment 2 was carried out to test the generality of this finding across grips and modes of transport.

Method

The same 4 subjects who participated in the experiment on point-to-point movement also participated in the experiment on cyclic movements. The same force transducer and accelerometer used in the point-to-point movements were also used in this experiment.

Experimental procedure. In the first part of this experiment, subjects produced vertical cyclic arm movements while holding the force transducer in one of the six grips illustrated in Figure 1. Three 3-s trials were collected for each grip. Subjects were asked to move at a moderate rate (between 1.5 and 2 Hz) and to produce fairly large amplitude movements. Movement amplitudes ranged between 30 and 40 cm. Targets were not presented, and there were no explicit accuracy requirements. Subjects were instructed to move in a straight line and to keep the orientation of the object constant. The movements were visually monitored by the experimenter during the experiment to ensure that the subjects complied with these instructions.

In the second part of the experiment, the subjects performed repetitive up and down jumping movements while holding the object with a precision grip. Subjects were asked to keep their arm joint angles constant. In other words, they were required to hold the object in a fixed position relative to their moving trunk.

Data analysis. Cross-correlations between load force and grip force were carried out to assess the overall phase relation between grip force and load force and the strength of the covariation between the two forces. In addition, the average time interval between grip and load force maxima was determined to see how well these maxima coincided in time. The relation between grip force and load force amplitudes was assessed by computing the ratio of the local grip and load force maxima in each movement cycle.

Results and Discussion

Figures illustrating individual records from 2 subjects are presented. As in the experiment on point-to-point movements, data from subject R.F. are shown in all of the figures so that direct comparisons can be made across tasks. Summary statistics are also presented. However, the focus is on qualitative patterns of grip and load force modulation.

Cyclic arm movements. Figure 7 shows grip force, acceleration, and load force records of cyclic arm movements while holding the objects with a precision (top), pincer (middle), or index finger (bottom) grip. Records obtained from subjects A.W. (left) and R.F. (right) are shown. Note that the acceleration maxima occurred at the point at which the hand was in its most downward position and the acceleration minima mark the points at which the hand was in its most upward position. The trials were selected so that, for each subject, the frequency and amplitude of load force fluctuation were similar across grips. The frequency of A.W.'s trials was about 1.5 Hz, and the maximum load force ranged from 10 to 13 N. The frequency of R.F.'s trials was about 2 Hz and the maximum load force was about 11 N. Similar results to those shown in this figure were obtained from all 4 subjects.

As shown in Figure 7, grip force was modulated almost perfectly in phase with load force, regardless of the grip

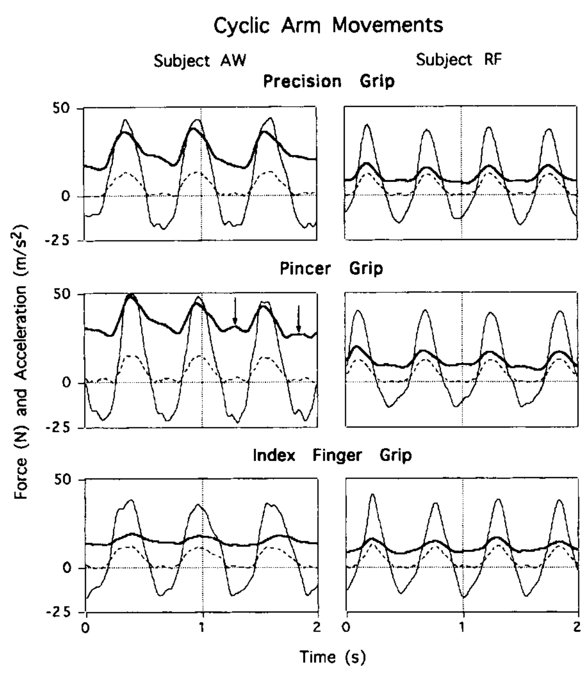

Figure 7. Single grip force, load force, and acceleration records from cyclic arm movements made while holding the object with a precision, pincer, or index finger grip.

used. A striking correspondence between grip and load force was observed throughout the movement cycle. Consider, for example, A.W.'s movement with the pincer grip. Because acceleration drops well below −g, clear peaks in load force coincide with the acceleration minima. Although these peaks are small in comparison to the large load force peaks coinciding with the acceleration maxima, corresponding peaks in grip force can be observed as indicated by the arrows in Figure 7. (Note that even when a clear peak was not observed, the grip force was heightened at this point.) The increased grip force at this time guards against the hand slipping down over the object as the object is accelerated downwards. Now consider R.F.'s movements and A.W.'s movement with the index finger grip. Here, the acceleration minima were close to −g. Thus, the load force coinciding with these minima was close to zero. In this case, an increase in grip force is not required, and clear peaks in grip force are not observed.

Note that both the mean level and amplitude of modulation of grip force in the precision and pincer grips were greater for A.W. than for R.F. Similar differences between subjects can be observed in the other figures. This may reflect differences in the coefficient of friction between the skin and the contact surface, which may be related to differences in sweating rate (Westling & Johansson, 1984). Cole (1991) has shown that skin friction tends to decrease with age. In this respect, it may be noted that A.W. was quite a bit older (47) than the other subjects (<34).

The tight temporal coupling between grip force and load force was also observed with the two inverted grips. The top two panels in Figure 8 show grip force, load force, and acceleration records from cyclic movements with the precision pirg for subjects R.F. and J.T. Note that, in these records, grip force and load force are 180° out-of-phase and that minima in grip force coincide with the load force maxima as expected. The same result was obtained with the thumbs pirg in all subjects.

Cross-correlations were carried out to determine the peak correlation (r) between load force and grip force and the time lag at which the peak r occurred. Table 5 presents the results for all six grips and for each subject. Each value is the average of three trials. Note that a positive time lag indicates that load force lagged behind grip force. The mean peak r values, averaged across subjects, were .91, .85, .88, and .88 for the precision, pincer, index fingers, and heels grips, respectively. The corresponding time lags were −3, −2, −21, and −2 ms. The mean peak r values for the precision and thumbs pirgs were −.78 and −.89, respectively, with time lags of −33 and −16 ms. Thus, on average, strong peak correlations were observed between grip force and load force, and there was very little phase lag between the force functions. Grip force tended to lag load force in 3 subjects but lead in one (R.F.). However, in all but two instances (A.W.'s index finger grip and S.K.'s precision pirg), the absolute lag was less than 30 ms. The low peak correlations observed in S.K.'s movements with the precision pirg were due to a tendency for the overall grip force to increase gradually during each trial.

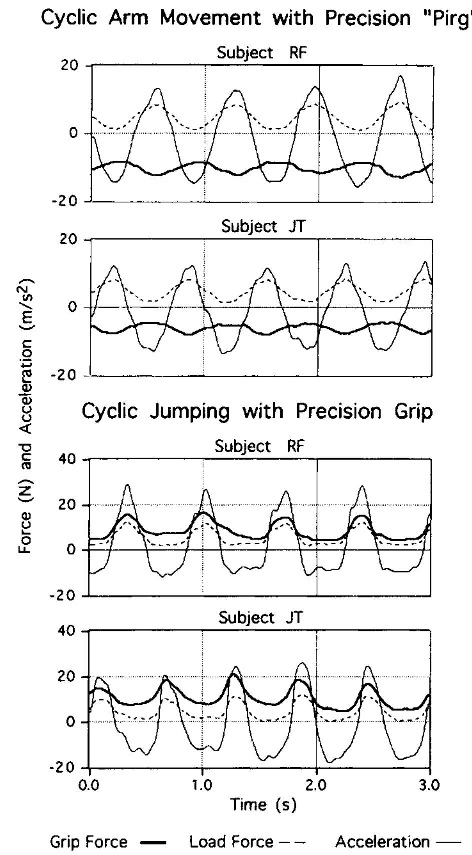

Figure 8. Top two panels show single grip force, load force, and acceleration traces from cyclic arm movements made while subjects R.F. and J.T. held an object in a precision pirg (inverted grip). The bottom two panels show single records for the same subjects obtained during repeated jumping with the joint angles of the arm held constant.

To further examine the timing of grip force and load force, the time between maximum load force and peak grip force was computed for each cycle. An average of about fourteen cycles were obtained for each subject × grip combination. Overall, maximum load force occurred just 3.2 ms after peak grip force and, with the exception of two cases, the absolute time between the peaks was less than 30 ms. The two exceptions were A.W.'s movements with the index finger grip (−71 ms) and S.K.'s movements with the precision pirg (−46 ms). Note that these were also the two cases where large cross-correlation lags were observed.

To assess the relation between grip force and load force magnitudes in cyclic movements, we also determined the ratio of maximum absolute grip force to maximum load force (GL_{max}) for each cycle and then computed means for each subject × grip combination. However, no clear pattern across subjects emerged. This may have been due in part to the fact that, in some subjects, movement frequency and maximum load force varied across grips. To explore the possible effects of movement frequency and maximum load

Table 5
Maximum Correlations (Max r) and Time Lags in Milliseconds at Which They Occurred, Obtained From Cross-Correlation of Grip Force and Load Force in Cyclic Arm Movements

	A.W.		J.T.		R.F.		S.K.	
Grip	Max *r*	Lag (ms)	Max *r*	Lag (ms)	Max *r*	Lag (ms)	Max *r*	Lag (ms)
Precision	.94	−10	.77	−10	.97	12	.94	−5
Pincer	.90	−2	.74	−15	.96	12	NA	NA
Index finger	.86	−62	.89	−10	.94	12	.81	−23
Heels	.86	−25	.93	−18	.85	22	.88	15
Precision pirg	−.81	−30	−.91	0	−.88	−20	−.53	−80
Thumb pirg	−.85	−17	−.87	−10	−.93	−17	−.90	−20

Note. Each value represents the mean of three trials recorded for each subject and grip. A positive time lag indicates that load force lagged behind grip force. Pirg = inverted grip; NA = not applicable.

force on GL_{max}, we focused on the results of the 1 subject (R.F.) who produced a range of frequencies and amplitudes across trials for each of the noninverted grips. (We excluded R.F.'s inverted grips because movement frequency varied little across trials.) We found that GL_{max} was positively and significantly correlated with movement frequency for each grip ($r > .54$, $p < .05$ in all cases). GL_{max} was also positively correlated with maximum load force in all grips, and the correlation was significant ($r > .7$, $p < .05$) in the precision and heels grips. Further work is currently underway to investigate more systematically how the relation of grip force to load force depends on movement frequency and load force amplitude.

To summarize the results thus far, we have shown that, regardless of the grip used, absolute grip force is modulated almost perfectly in phase with load force during cyclic movements with a hand-held object. The tight temporal coupling can be observed either by examining the timing of key features (e.g., the lags between grip and load force peaks in each cycle) or the waveform as a whole (i.e., cross-correlation analysis).

Cyclic jumping movements. Thus far we have described how grip force is modulated in phase with changes in load force produced by arm movement. We now consider how grip force is modulated to deal with fluctuations in load force induced by jumping with the arm's joint angles held constant. The bottom two panels of Figure 8 show grip force, load force, and acceleration traces from single trials in which the subject jumped up and down repeatedly while holding the object with a precision grip. Records from subjects R.F. and J.T. are shown. As in the case where the object was transported by moving the arm (see Figure 7), grip force is modulated in phase with load force. Cross-correlation analysis revealed a maximum correlation of .94 at a lag of 5 ms for the trial shown for subject R.F. Similar results were obtained in all three trials for all subjects. The largest absolute lag was 30 ms, and the lowest maximum correlation was .78. These results indicate that the parallel modulation of grip force and load force observed in cyclic movements does not depend on the articulators producing the motion.

General Discussion

In previous work, we have shown that grip force and load force are tightly coupled during arm movements with objects held in a precision grip (Flanagan et al., 1993; Flanagan & Wing, 1993). In this article, we have shown that grip and load forces are also tightly linked during arm movements with a variety of different grips and during whole body jumping movement with a precision grip. The results show that grip force is modulated in anticipation of changes in load force generated by active movements, regardless of the grip and mode of transport.

The invariance of the qualitative pattern of grip–load force coupling across grip types and modes of transport indicates that there is a general strategy for coordinating grip and load forces during active transport of a held object. This strategy or mechanism applies to all sorts of grips, including two-handed and inverted grips, and does not depend on the articulators moving the object.

To examine further the ability of the grip force control system to take account of both body and arm movements, we asked our subjects to jump up and down while holding the position of the object at a fixed position in space. This required the subjects to produce concurrent arm and whole body movements. We observed that the amplitude of grip force modulation depended on the acceleration of the object. In trials where the acceleration was close to zero throughout, almost no variation in grip force was observed even though the subject had to move the arm quite rapidly in order to hold the object steady. This observation suggests that the grip controller intelligently incorporates movements of the arm and body. Grip force is only modulated when the net result of all movements leads to object acceleration and, consequently, fluctuations in load force.

Although the coupling of grip force and load force was qualitatively similar in all grips, the temporal coordination of grip force and load force was more variable in the precision pirg. This may reflect the impoverished tactile information in this grip. Johansson and Westling (1984) have shown that glabrous skin afferent receptors provide information that is used to update grip force parameters when lifting objects with a precision grip. Thus, the greater variability observed in the precision pirg may reflect poor sensory feedback, which, in other grips, plays an important role in fine-tuning grip force.

Research into the coordination of anticipatory grip aperture formation and hand transport movements indicates that these two functionally independent actions are temporally coupled when reaching out to grasp a stationary target object. Because the grip aperture is not formed before the reaching movement begins and there is only one reaching movement, some temporal coupling is to be expected: The anticipatory formation of the grip aperture must be completed during the transport movement. This could be done simply by initiating aperture formation and movement at the same time and scaling the grip formation movement time to the transport movement time. Such a scheme could produce the pattern of spatiotemporal correspondences between phases of grip formation (e.g., maximum aperture size) and transport movement (e.g., peak velocity), which are observed in unconstrained prehension (e.g., Haggard, 1991; Jeannerod, 1981, 1984). However, the two components would not actually be influencing one another and hence would not be coupled during the actual execution of the action. Such a scheme was favored by Jeannerod (1981, 1984).

The most effective way to determine whether the two components are coupled is to perturb one component and look for effects on the other. Perturbation studies by Haggard (1991; Haggard & Wing, 1991) have shown that the relationship between transport and grasp components tends to be preserved after mechanical perturbations to the reaching limb: The perturbations led to compensatory adjustments in both transport and grasp components. Thus, Haggard concluded that there is a coupling of the two components during prehensile movements, which tends to act to preserve an invariant spatiotemporal relationship between them (Haggard, 1991; Haggard & Wing, 1991): Anticipatory grip formation and hand transport appear to be planned and controlled as a "unit" during prehension. It is clear from the data we report here and elsewhere (Flanagan et al., 1993) that gripping and transporting are likewise planned and controlled together when a person moves a held object and that this synergy is established at a level of representation independent of the actual articulators that will actually do the gripping and transporting—something that has not been empirically documented for prehension. It is also interesting to note that although the coordination between anticipatory aperture formation and the reaching movement in prehension can be abolished voluntarily, it does not appear to be possible to abolish the coordination of grip force and load force in the tasks we have examined (Flanagan & Wing, 1993).

The various accounts of how grasp–transport coordination is achieved during prehension involve one or other or both of two kinds of coordination mechanism—a preplanning type mechanism (with or without a central feedforward component) and a feedback type mechanism. The functional organization of these types of mechanism are shown schematically in Figure 9a and 9b. An example of the preplanning mechanism with feedforward is Jeannerod's (1981, 1984) model: The grasping and transport components operate more or less independently during execution of the action but are driven by a common central program, which determines the timing of the various movement phases of the two components so achieving coordination ("a centrally generated temporal template," Jeannerod, 1984, p. 252). An alternative, indicated in Figure 9a, is that the central mechanism generates no feedforward signal but simply parameterizes the grip and transport controllers so that they generate temporally coordinated outputs.

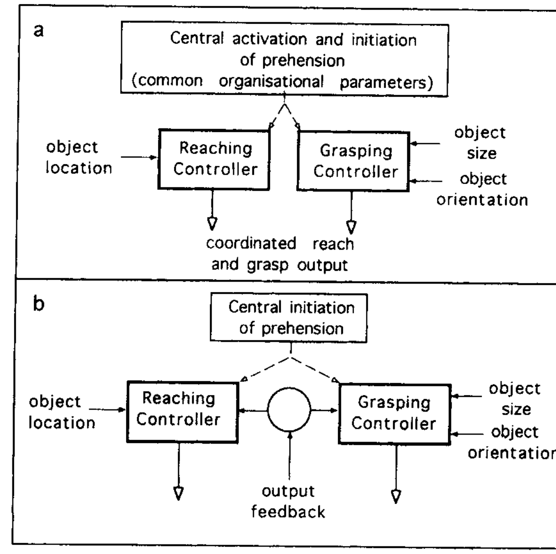

Figure 9. a: Functional block diagram of a feedforward model of the coordination of grasp and transport components of prehension movements. b: Block diagram of a feedback or "sensor-driven" model of grasp and transport coordination in prehension.

Examples of a feedback type mechanism are provided by Bootsma and van Wieringen (1992) and by Haggard (1991). Both regard the observed grasp–transport coordination to be the result of their being controlled by a common source of sensory information; Haggard refers to this as sensor-driven coordination. Haggard's proposal is the far better developed of the two because he develops and simulates a model, whereas Bootsma and van Wieringen merely suggest that such a feedback mechanism might be the basis of coordination. Haggard's model uses information about the position of the hand relative to the target and is quite successful in simulating observed patterns of data. Bootsma and van Wieringen, however, suggest that information about the time to contact (assuming constant velocity) of the hand with the target might be used. Because hand velocity is not constant and Bootsma and van Wieringen do not develop a model, it is unclear whether their scheme can successfully model the data.

An alternative type of model in which feedback plays a major role has been put forward by Hoff and Arbib (1993). This model involves coordinating grasp and transport components through estimates of the time needed to complete the transport component and the time needed to complete the aperture preshaping movement. Estimates of these required times are computed by grasp and transport control modules, which each received various kinds of feedback information and use this in computing the required times. This model does not involve sensor-driven coordination. Instead, the grasp and transport controllers interact through the required times in such a way that both movements are scaled to the longer duration.

The data that we have presented here and elsewhere suggest alternative versions of the feedforward and feedback type control schemes. In the alternative feedback scheme, sensory feedback is assumed to provide information that anticipates the future state of the effector system, rather than simply providing information about the current state of the system. Anticipatory visual information is likely to be important in jumping where the subject must anticipate when he or she will land so that the grip force reaches its maximum at this point. It is clear from existing data that visual information is used to "tune" the body in anticipation of landing (e.g., Dietz & Noth, 1978; Sidaway, McNitt-Gray, & Davis, 1989). Similarly, as reported by Johansson et al. (1992), when an object is dropped into a cup held by the subject the grip force increases in anticipation of the load perturbation caused by the object contacting the bottom of the cup. In both these cases, the required magnitude of grip force increase will depend on momentum—the momentum of the ball in the catching in a cup task, and the momentum of the held object in the jumping task.

Nonvisual anticipatory information could be derived from feedback from sensors in the muscles and joints of the effector system. One possible type of anticipatory information that would be useful in controlling grip force is suggested by the work of Kelso (1986). The state of any system with two phase variables (e.g., position and velocity) that is passing repeatedly through a cycle of states (an oscillating system) can be specified at any time by a single phase angle and a radial amplitude relative to a coordinate system fixed in the phase plane. If the system moves round its cycle of states with constant phase velocity, $\dot{\phi}$, then the tau-function (Lee, 1992) of the phase angle, $\tau(\phi) = \phi/\dot{\phi}$, is the time-to-contact of the system with the state at which $\phi = 0$.

Imagine that the hand is the oscillating system and is adequately described by a position and a velocity. If the muscle-point receptors in the limb can supply sufficient information to compute the quantity $\tau(\phi)$ for the hand, the person has access to (approximate) information about how long it will be before the hand reaches the zero phase angle state. This zero state could be arranged to be that state where the load force is greatest and hence the grip force needs to be greatest. In this way, the grip force controller could arrange for grip force development to proceed such that it reaches its maximum in a time equal to that specified by the value of $\tau(\phi)$. Note, however, that computation of $\tau(\phi)$ for the hand is not altogether straightforward, because it must be derived from joint and muscle sensors throughout the arm. It would appear, therefore, that a model of the arm's geometry is required. Moreover, the signals from muscle and joint receptors cannot be interpreted without central command (efference copy) information (see, e.g., Feldman & Latash, 1982).

Figure 10a shows the organization of the feedforward mechanism: The transport controller not only sends its output to the neuromuscular system but also to the grip controller. The output to the grip controller is a feedforward signal, which can be used to generate a pattern of grip force modulation that anticipates the modulation in load force that results from the transport movement. This type of feedforward differs from that proposed in models of preshaping-transport coordination, because the transport and grip controllers are not both driven by the same feedforward signal.

Figure 10b outlines a transformation between arm transport, specifically arm acceleration, and grip force. The time varying acceleration due to arm movement and the gravitational acceleration (g) are summed, multiplied by the mass and rectified to give load force. Load force is then low-pass filtered and multiplied by a grip–load ratio that is expected to depend on the friction coefficient of the gripped surfaces of the object and on a person's experience (Johansson & Westling, 1988). An additional offset may be required if the grip–load ratio is not constant throughout the movement. Note that we do not hold the view that the central nervous system specifies acceleration in the control of movement. We would favor the view that the arm acceleration signal would be derived from a centrally specific trajectory of end-effector equilibrium positions (Bizzi, Accornero, Chapple, & Hogan, 1982, 1984; Feldman, 1974; Flash, 1987). Knowledge of limb and object dynamics would be

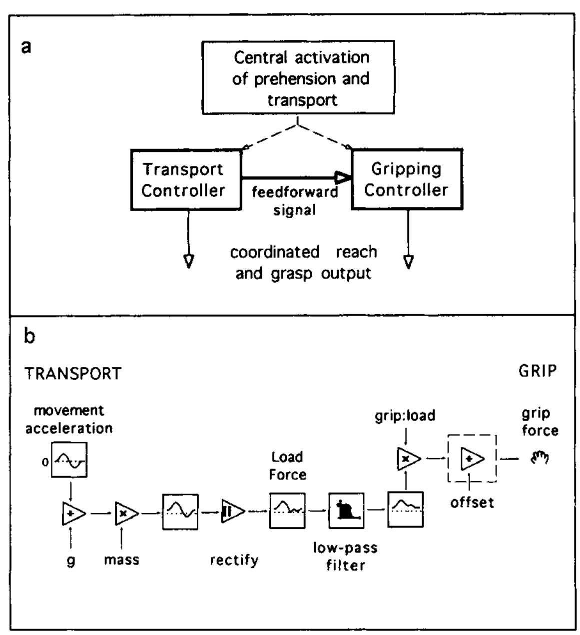

Figure 10. a: Functional block diagram of the feedforward control of grip force model described in the text. b: A simple model of one possible transformation between an acceleration signal and grip force (see text for details).

required to estimate the object's actual acceleration from the equilibrium trajectory.

The operation of the simple model relating acceleration and grip force shown in Figure 10a is illustrated in Figure 11. The top panel shows grip force and load force from one of subject R.F.'s cyclic arm movements with a precision grip. In the middle panel the dashed trace represents load force low-pass filtered at 3.5 Hz and scaled by a grip–load ratio factor of 1.9. This scale factor was selected such that the peaks were about equal in magnitude. Finally, in the bottom panel the dashed trace is load force again low-passed at 3.5 Hz but then scaled by a factor of 1.3 and offset by 5.5 N. As can be seen, the full transformation of load force depicted in the bottom panel provides an excellent fit to the observed grip force. Thus, if the grip force planner has access to accurate feedforward information about the expected load force, the grip force can be modulated to follow the load force during movement using a transformation mechanism like that shown in Figure 10b.

A second point can be made from Figure 11. The result shown in the middle panel of Figure 11b indicates that the grip–load ratio is not constant during cyclic movements. If it were, then a good fit to grip force should be obtained simply by scaling the (filtered) load force. A scale factor of 1.9 is able to produce matched peaks, but the troughs do not coincide. Thus, the grip–load ratio is greater when the load force is smaller. This finding that the ratio increases as load decreases is not inconsistent with the results of Johansson and Westling (1984), which show that when lifting an object the grip–load ratio is increased at the very start of the lift when the load force is small.

In conclusion, we have provided evidence that the coupling of grip force and load force reflects a general control strategy for transporting objects that is observed across a variety of grips and modes of transport. The tight linkage between grip force and load force suggests that the control signals underlying object transport may be used, together with information of object and articulator dynamics, to specify grip forces.

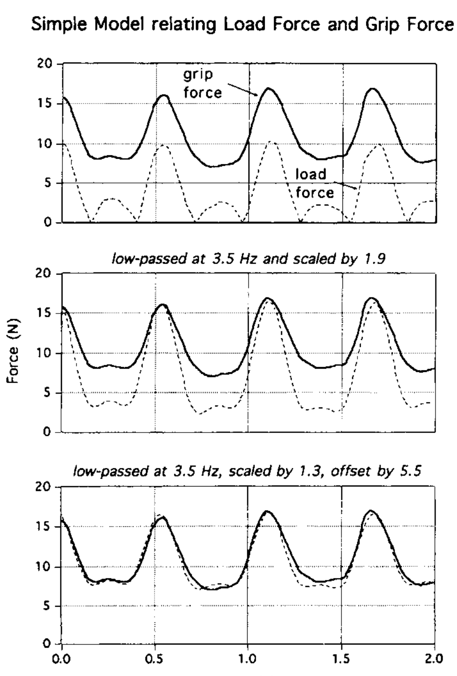

Figure 11. Implementation of the simple model shown in Figure 10b. The top panel shows grip force and load force recorded from subject R.F. during a cyclic arm movement with a precision grip. The middle panel shows grip force (thick line) and load force after low-pass filtering and scaling (dashed line). The bottom panel shows grip force (thick line) and load force after low-pass filtering, scaling, and offsetting (dashed line).

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P&C Board Appoints Editor for New Journal: *Journal of Experimental Psychology: Applied*

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Areas of interest include applications of perception, attention, decision making, reasoning, information processing, learning, and performance. Settings may be industrial (such as human–computer interface design), academic (such as intelligent computer-aided instruction), or consumer oriented (such as applications of text comprehension theory to the development or evaluation of product instructions).