ANTICIPATING DYNAMIC LOADS IN HANDLING OBJECTS.

Alan M. Wing
Sensory Motor Neuroscience Centre,
The University of Birmingham,
Edgbaston, Birmingham, B15 2TT, UK.
a.m.wing@bham.ac.uk

J. Randall Flanagan
Department of Psychology,
Queen's University,
Kingston, Ontario, Canada.
flanagan@psyc.queensu.ca

DSC-Vol 64, Proceedings of the ASME Dynamic systems and Control Division, ASME 1998, 139-143

SUMMARY

In this paper we review a set of studies showing that when people pick up and move an object they continually adjust their grip force in order to stabilize the object in the hand. These grip force adjustments occur simultaneously with or slightly ahead of fluctuations in load forces and torques related to moving the object. They may therefore be seen as anticipatory and we argue that a key line of research in manipulation should be to understand the integration of sensory motor information to build an internal model of the object and the effector system to support such anticipation.

LIFTING AND HOLDING

Consider picking up and holding an object with parallel sides, such as a glass tumbler, using a precision grip with the thumb and one or more fingers pressing in on opposite sides. Frictional force, generated by grip force normal to the surfaces, is used to overcome load forces tangential to the surface which would otherwise result in the hand slipping over the surface of the glass. Up to the point at which the glass lifts off the surface the load force depends on the lift developed by the arm. After lift-off the load force is generally determined by the combined effects of gravity and any acceleration of the hand used in moving the object. In order to stabilize the object in the hand and prevent slip a minimum level of grip force is required which is a function of the tangential load and the frictional properties of the hand-object interface.

With a wealth of sensory information available from tactile receptors in the skin, it might be thought that stabilization of an object in the hand would involve feedback adjustment of grip force. As the arm muscles begin to develop forces to lift the hand and object off a support surface or to accelerate the hand and object from rest, the resulting shear or tangential load force at the finger tips might drive an increase in grip force. However, the reflex pathways involved would introduce a delay of around 80 ms and are too slow to guarantee grasp stability. Instead, in familiar situations where loading is predictable, grip force is typically adjusted in phase with changes in load force.

To study force coordination in lifting Johansson and Westling (1984) asked subjects to use a precision grip to lift an instrumented manipulandum a small distance off a support while the surface slipperiness was systematically varied (in decreasing order of slipperiness - silk, suede, sandpaper). In all cases they noted that grip force started to rise before load force. Load force then started to rise and, provided subjects were familiar with the lifting conditions, the ratio of grip force to load force decreased to a value somewhat above the minimum, given the surface, required to prevent slip (thus defining a 'safety margin' against slip, Westling and Johansson, 1984). As load force continued to rise the force ratio remained approximately constant until the object was lifted from the surface. Although quite different levels of grip force were required for the different surfaces, Johansson and Westling found that the time taken to lift the manipulandum off the surface was relatively constant, provided subjects knew the surface in advance. This timing constancy was achieved by scaling the rate of increase of grip force from the outset and constitutes strong evidence of anticipatory control.

MOVING

During static holding, grip force typically exceeds the minimum to prevent slip by a safety margin which can be as small as 10%. In moving an object, peak accelerations can easily reach twice the acceleration due to gravity, which results in a significant fluctuation in load force superimposed on the steady contribution of gravity. We have studied modulation of grip force associated with load force fluctuations due to arm movements when holding an object in precision grip (Flanagan et al, 1993; Flanagan and Wing, 1993, 1995). In the case of vertical movements, the summation of inertial and gravitational forces results in load force functions that reach their maximum near the start of upward movements but near the end of downward movements. Because grip force functions for up and down movements reflect this contrast, Flanagan and Wing were able to argue that grip force adjustments are anticipatory of loading and not simply linked to movement per se (see also Wing, 1996).

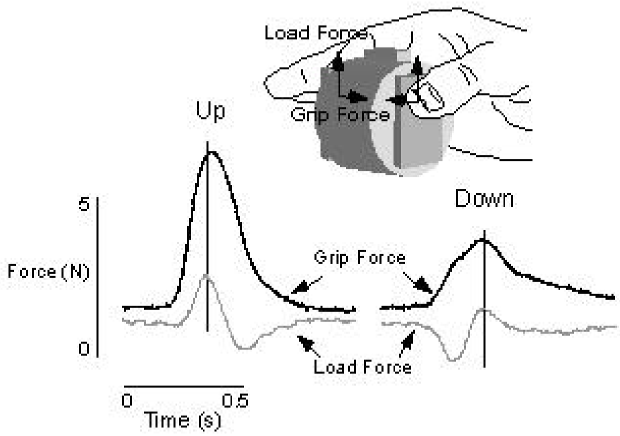

Fig 1: Modulation of grip force when moving an inertial load held between the tips of the thumb and index finger. The load force pattern varies depending on whether the object is moved up (left) or down) and this is reflected in the grip force pattern. Illustrative single trial data adapted from Flanagan, Tresilian & Wing, (995).

In the previous study the load force was inertial and so directly related to acceleration and deceleration. The effect of load force functions related to other parameters of movement on grip force was examined by Flanagan and Wing (1997). Subjects grasped a manipulandum that was mounted on a linear motor. The motor could be servo-controlled to produce load force functions that, in different blocks, were primarily inertial, viscous (load proportional to velocity) or elastic (load proportional to position). It was observed that the form of the hand trajectory changed with load for some subjects but not for others. However, under all load conditions and in all subjects, grip force was modulated in parallel with, and thus anticipated, fluctuations in load force (see Fig. 2). The adaptation of grip force to changes in load force was taken as evidence of the operation of an internal model of the dynamics of the motor apparatus and external load.

In holding an object with a precision grip, the grasp axis joining the points at which the two digits make contact with the object may not be accurately aligned with its centre of mass. In such cases gravitational and/or inertial forces will result in torques at the digits and stabilization of the object is a matter of preventing it rotating, as well as translating, within the hand. Wing and Lederman (In Press) have shown that subjects anticipate, and attempt to compensate for, such load torques when lifting or moving an object with the hand by increasing grip force in proportion to the distance between the grasp axis and the centre of mass. Again an internal model of the effector system and external load would provide abasis for such prediction

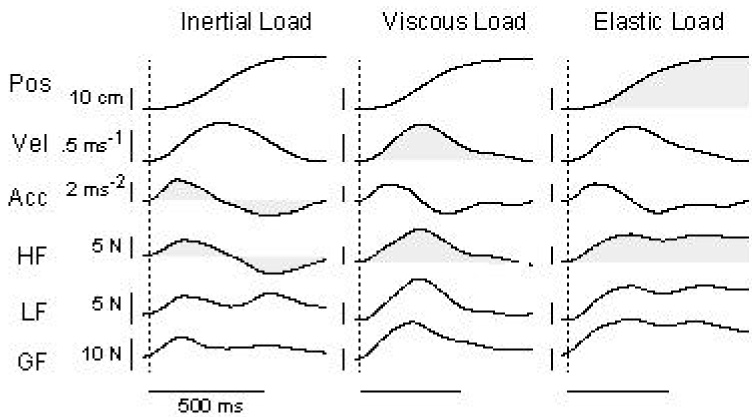

Fig 2: When force at the hand (HF) is related to acceleration, velocity of position, grip force (GF) modulation is adapted to different load force (LF)f unctions . Illustrative single trial data for one subject (Flanagan & Wing, 1997).

ADAPTING TO CHANGES IN LOAD

Anticipatory stabilization of hand-held objects is evident when subjects are familiar with the conditions and/or vision provides cues sufficient to retrieve information remembered from previous experience with the conditions. However, an important question is how that information is acquired and this leads to consideration of adaptive changes in performance when task conditions change.

In Johansson and Westling's (1984) experiment on lifting, the slipperiness of the contact surfaces of the manipulandum was systematically varied. After a block of trials with one surface the experimenters changed the surface for the next block of trials. In this situation the grip force initially rose at a rate appropriate to the surface used in the previous block of trials but was then adjusted. When the change was to a more slippery surface, an inadequate level of grip force resulted in a small slip which led to a rapid corrective increase in grip force. On the next trial the grip force rate would rise appropriately from the outset. Subsequently, Johansson and Westling (1988a) showed similar adaptation to unexpected changes in object weight. Findings such as these led to the suggestion that force coordination in lifting is based on sensory motor memories which represent physical properties of objects and appropriate magnitude parameters of the motor commands (see Johansson, 1996). These memories are presumably updated whenever inappropriate motor commands based on erroneous information result in unintended mechanical events such as slip.

Flanagan and Wing's (1997) analysis of grip force adaptation to different load force functions focused on stable performance. However, short-term changes in hand trajectory were seen immediately after the change in load force condition (Flanagan and Wing, 1996) and certain interesting points emerge from consideration of such changes. Figure 3 shows grip and load force and their ratio for one subject over the first 8 trials (a-h) immediately after changing from the inertial to the viscous load. It will be observed that the load force function evolves from a multi-peaked profile to a single smooth function which is very similar to the superimposed profiles from the last 10 trials (i). This suggests the subject was gradually becoming familiar with the changed dynamics of the system.

It is particularly interesting to note that despite the major changes in load force function, the match between grip force and load force is good from the second or third trial. This tendency was observed in several subjects and the lower part of Fig. 3 summarizes this in terms of correlations (averaged across the group) between grip force and load force functions (j) and between the load force function on a given trial and the average of the last 10 trials (k). The latter takes longer to settle at a steady value than does the correlation between grip force and load force.

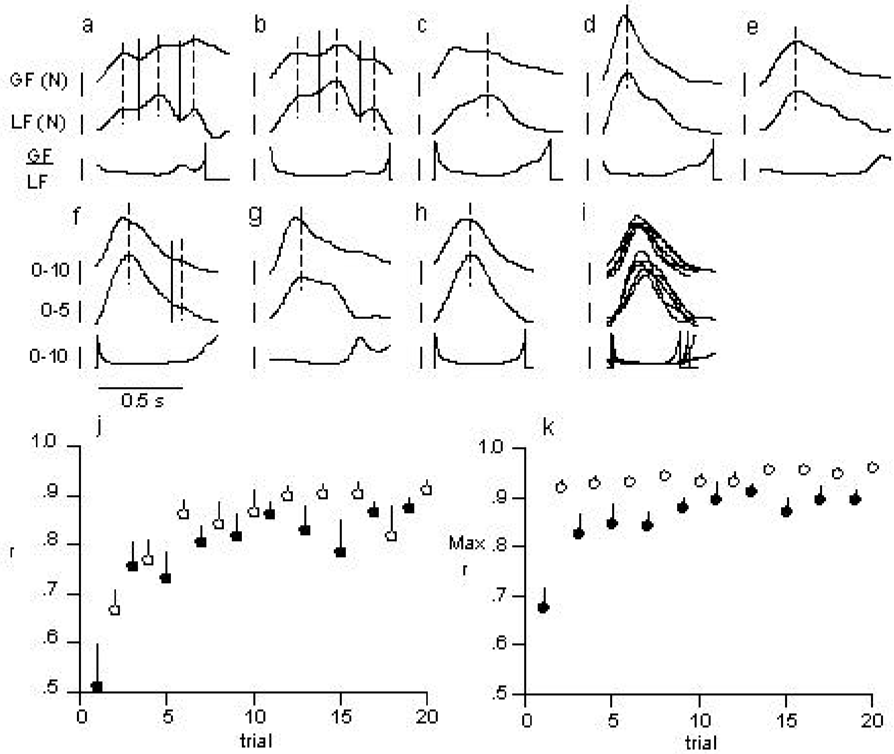

Fig 3: Adaptation to viscous load: (a-h) Load force functions converge on form evident in last 10 trials (i); illustrative single trial data from one subjet. Group average correlations (j-k) between (j) LF on the first 20 trials and the average of trials 20-30 (k) GF and LF suggest GF and LF function develop similarity more rapidly than the rate at which LF converges on its final form (Flanagan & Wing, 1996)

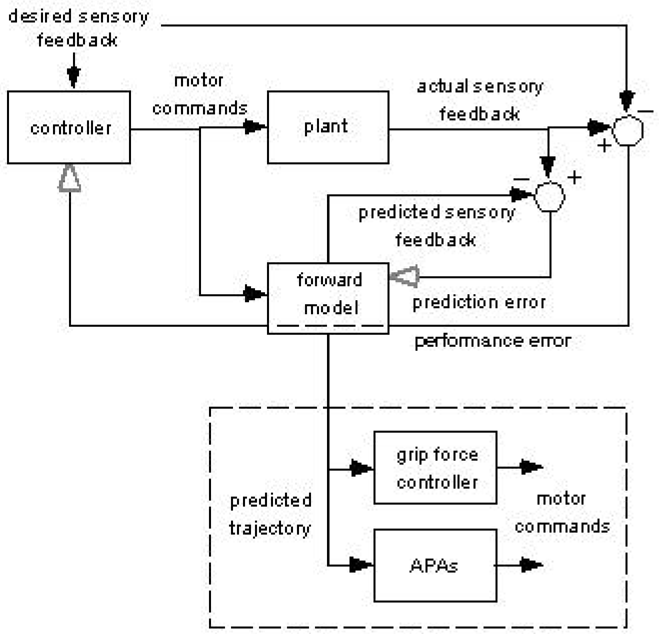

Fig 4: Forward model for learning arm movement control and predicting the grip force function necessary for object stabilization (Flanagan & Wing, 1996).

One interpretation of this finding is that the hand controller was able to predict the load force before learning the commands required to generate smooth movements. A possible scheme based on Jordan and Rumelhart (1992) is shown in Figure 4 (Flanagan and Wing, 1996). As in their original exposition, muscle commands from the controller are entered into a forward model which predicts sensory consequences. The discrepancy between observed and predicted sensory consequences can then be used to train the controller. However, the output of the forward model might also be used to determine the level of grip force required to provide a stable grasp. In this perspective, the importance of sensory feedback is not just in reacting to unpredictable load forces but also for updating and fine-tuning anticipatory control mechanisms in case the unpredictability reflects changes in the dynamics of the environment which, once learned, will allow control to revert to an anticipatory basis.

Given the evidence favouring the existence of an internal model it is natural to ask what are the underlying neural mechanisms? Miall et al (1993) have suggested a cerebellar contribution to learning of hand aiming movements in the form of two internal models. A forward model of the motor apparatus predicts the sensory consequences of motor commands and a second model predicts time delays in the control loop in order to delay the predicted sensory feedback so that it can be directly compared with actual sensory feedback. The error signal from this comparison may then be used to modify motor commands and update the first model. Miall et al describe how this model predicts certain failures of hand aiming movements after cerebellar damage. If the internal model for arm movement also provides the basis for anticipatory adjustment of grip force cerebellar damage might also be expected to affect grip force control. Some support for this suggestion comes from a study by Muller and Dichgans (1994). Patients with degenerative cerebellar conditions exhibited impaired coordination of grip force and load force in lifting objects. Moreover they failed to scale their grip force rates to different loads. A possible interpretation therefore is that the performance impairment reflects a flawed internal model due to the cerebellar damage.

CONCLUSIONS

Anticipatory adjustments of grip force in lifting and moving objects suggest the operation of an internal model of the effector system and the object. An important function of sensory feedback during object manipulation may therefore be to provide a basis for maintaining the internal model under changing environmental conditions.

REFERENCES

Flanagan JR, Tresilian JR & Wing AM (1993) Coupling of grip force and load force during arm movements with grasped objects. Neuroscience Letters, 152, 53-56.

Flanagan JR, Tresilian JR & Wing AM (1995) Grip force adjustments during rapid hand movements suggest that detailed movement kinematics are predicted. Behavioral and Brain Sciences 18: 753-754

Flanagan, J.R & Wing, A.M. (1993) Modulation of grip force with load force during point to point arm movements. Experimental Brain Research, 95, 131-143.

Flanagan, J.R. & Wing, A.M. The stability of precision grip forces during cyclic arm movements with a hand-held load. Experimental Brain Research, 1995, 105, 455-464.

Flanagan, J.R. & Wing AM (1996) Internal Models of Dynamics in Motor Learning and Control. Paper presented at the 26th Annual Meeting of the Society for Neuroscience, Washington, DC, Soc Neurosci Abstr, 22, Part 2, p 897

Flanagan, J. R., & Wing, A.M. (1997). The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. Journal of Neuroscience, 17, 1519-1528.
Johansson, R.S. (1996). Sensory control of dexterous manipulation in humans. In A.M. Wing, P. Haggard & J.R. Flanagan (Eds) Hand and Brain: The neurophysiology and psychology of hand movements. San Diego: Academic.
Johansson, R. S. & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. Experimental Brain Research, 56, 550-564.
Johansson, R. S. & Westling, G. (1988a). Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting with precision grip. Experimental Brain Research, 71, 59-71.
Johansson, R. S. & Westling, G. (1988b). Programmed and triggered actions to rapid load changes during precision grip. Experimental Brain Research, 71, 72-86.
Johansson, R. S. (1996) Sensory control of dexterous manipulation in humans. In A.M. Wing, P. Haggard & J.R. Flanagan (Eds) Hand and Brain: The neurophysiology and psychology of hand movements. San Diego: Academic.
Jordan, M.I. & Rumelhart, D.E. (1992) Forward models: supervised learning with a distal teacher. Cognitive Science, 16: 307-354.
Miall, R.C., Weir, D.J., Wolpert, D.M. & Stein, J.F. (1993) Is the cerebellum a Smith predictor? Journal of Motor Behavior, 25, 203-216.
Westling, G. & Johansson, R. S. (1984). Factors influencing the force control during precision grip. Experimental Brain Research, 53, 277-284.
Wing, A.M. (1996) Anticipatory control of grip force in rapid arm movement. In A.M. Wing, P. Haggard & J.R. Flanagan (Eds) Hand and Brain: The neurophysiology and psychology of hand movements. San Diego: Academic.
Wing, A.M. & Lederman, S. Anticipating load torques produced by voluntary movements. Journal of Experimental Psychology: Human Perception and Performance (In Press).