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Coupling of grip force and load force during arm movements with grasped objects

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Numerous studies have investigated the kinematics of arm movements; others have examined grip forces during static holding of objects. However, the coordination of grip force and arm movement when moving grasped objects has not been documented. We show that grip force is finely modulated in phase with load force during movements with grasped objects in which load force varies with acceleration. A tight coupling between grip and load force is seen in point-to-point and cyclic movements of varying rate and direction. We conclude that in transporting an object, the programming of grip force is part and parcel of the process of planning the arm movement.

When an object is held with the thumb and index finger squeezing the sides, a grip force (directed into the surface of the object) must be applied to prevent slipping. Raising the grip force increases the friction between the object and finger pads and enables a heavier or more slippery object to be held. In static holding, grip force is typically slightly higher than the minimum grip force required to prevent slipping. The ratio of excess grip force to minimum required grip force is approximately constant for objects of varying weight and slipperiness. This led Johansson and Westling [4] to speak of a safety margin that guards against random fluctuations in the motor system or relaxation of grip due to, for example, fatigue.

When an object is moved, a force must be applied to overcome its inertia. The force tangential to the object's surface (the load force) is then a combination of gravitational force and an inertial force proportional to the acceleration of the object. Given that the safety margin for static holding is not large, an increase in grip force may be required during movement. The question arises as to how grip force is modulated during the movement. One possibility is that grip force varies in a time-dependent fashion with load force. On the other hand, grip force might be raised to a constant level throughout the movement, high enough to ensure that the object does not slip.

In this paper, we examined grip forces used to hold an object during point-to-point and cyclic movements some 20–40 cm in amplitude. The subjects grasped the flat ends of a cylindrical force transducer (Novatech, model 241) of mass 0.25 kg using a precision grip with the pads of the thumb and index finger pressing against metal plates 58 mm apart. An accelerometer (Entran, model EGB-125–10D) taped to the force transducer was used to determine load force. Vertical and horizontal movements were examined. However, the direction of movement relative to the orientation of the grasp was constant. The object was always moved in a direction approximately orthogonal to the plane defined by the the thumb and index finger and with the contact planes oriented vertically.

Point-to-point movements: Fig. 1 shows patterns of grip force obtained during point-to-point movements made vertically and horizontally. The component of load force in the direction of movement is also shown. In vertical motions, both gravitational and inertial forces act in the direction of movement. Thus, the vertical load force represents the total load force on the object. In contrast, for horizontal motions the force due to gravity and the inertial force are orthogonal and the horizontal force is purely inertial. Note that in point-to-point movements, trials begin and end with the subject holding the object up in the air at rest.

Consider first the vertical movements. When the object is moved up, the vertical force exhibits a maximum (as the object is accelerated up) followed by a minimum

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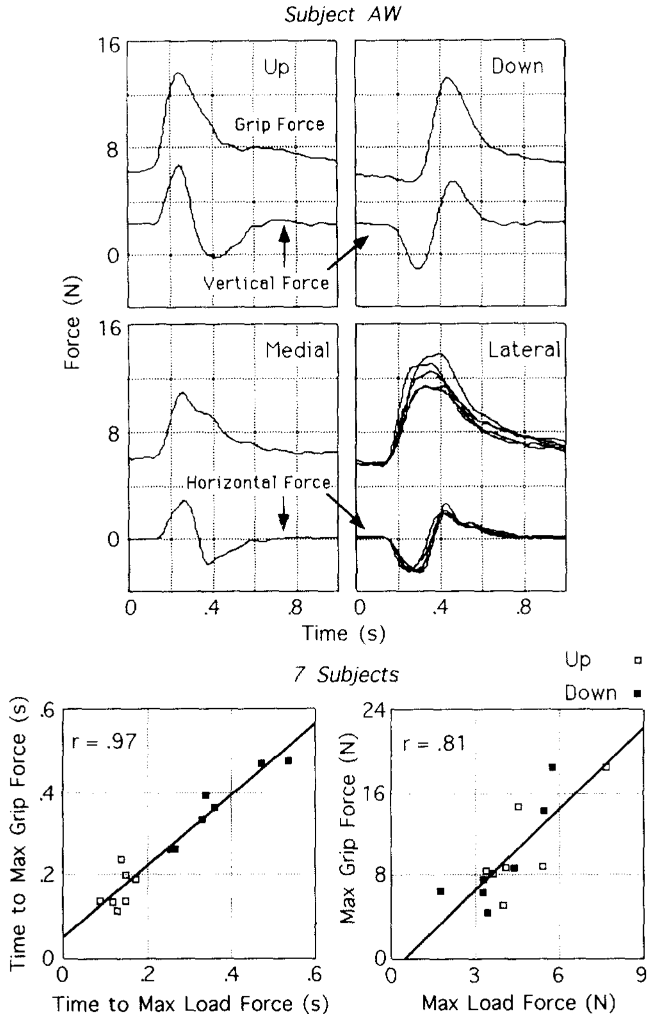

Fig. 1. Coupling of grip force and load force acting in the direction of motion during point-to-point movements. Each of the top four panels shows grip force and vertical or horizontal load force for single trials when a subject (AW) moved the force transducer in one of four directions. Several trials are shown for the lateral movement. Data were recorded at 200 Hz and low-pass filtered with a cut-off of 14 Hz. In the vertical movements there is a maximum in grip force that coincides with the vertical force maximum. This occurs near the start of the upward movement and towards the end of the downward movement. In contrast, there is no increase in grip force associated with the vertical force minimum which is near zero. In horizontal movements grip force is elevated for both the maxima and minima of horizontal force. In the bottom left panel, time to maximum grip force is plotted against time to maximum load force. Data are from single up and down movements made by seven subjects. In the bottom right panel maximum grip force is plotted against maximum load force for the same movements.

(as it is decelerated). The grip force shows a clear maximum at the time of maximum vertical force and then drops back to a steady level towards the end of the movement. The increase in grip force compensates for the increase in vertical force due to the movement. In contrast, there is no increase in grip force coinciding with the vertical force minimum; indeed, there is sometimes a small dip.

In the movement down, grip force again shows a clear maximum coinciding with the maximum vertical force. The increase in grip force prevents the object from slipping during the sharp braking towards the end of the movement. There is a small dip in grip force associated with the initial vertical force minimum. A grip force lower than baseline is possible here without slippage because the vertical load force is reduced to near zero.

We now consider medial and lateral movements where the horizontal force fluctuates on either side of zero. As in the case of vertical motions, grip force is clearly modulated during the movement. However, a rapid rise in grip force is now seen in both directions, regardless of whether the initial peak in horizontal force is a maximum or minimum. Moreover, grip force remains elevated, or even shows a second peak, during the subsequent minimum or maximum in horizontal force. In other words, in sideways movements, elevated grip forces are associated with both the initial acceleratory and the subsequent deceleratory phases of the movement. Note that in sideways movements, peaks in load force (i.e., the magnitude of the total force acting on the object) of similar amplitude are seen during both phases. In contrast, vertical movements usually exhibit a single predominant load force peak.

To quantify the coupling observed between grip and load force in point-to-point movements, we correlated times of grip force and load force maxima over trials. Times were relative to movement onset taken as the time at which load force exceeded 2 SDs from the mean resting level. The force maxima were also correlated. Data from up and down movements of varying rate were combined. Strong positive correlations between maxima times were observed across trials (n=20) for single subjects (RF: r=0.99; AW: r=0.98) and across a group of seven subjects (group: r=0.97). The data for the seven subjects are from their first trials. However, the relation was weaker for force magnitudes (RF: r=0.81; AW: r=0.87; group: r=0.81). Tight temporal linkage between grasp and arm movement has also been observed in other tasks. For example, anticipatory changes in hand shape while reaching for an object have been found to be temporally coupled to the arm movement [2, 3, 9–11].

The coupling observed between grip and load force reflects a soft-assembled neural synergy rather than simply a mechanical artifact due to muscle lines of action. When we applied an unexpected load to the object with grip force already sufficient to prevent slip, we found no increase in measured grip force until around 70 ms later by which time sensori-motor loop involvement would be expected (see also refs. 1 and 5). This finding indicates that there is no mechanical consequence of applying a load such as drawing in the thumb or finger. If the coupling between load and grip force were mechanical, then we would expect grip force to increase immediately after the unexpected loading.

Cyclical movements: The modulation of grip force during cyclical movements is particularly striking (Fig. 2). In both up and down and side-to-side movements, grip force and load force are modulated in phase. Cross-correlation of grip force and load force in the vertical case revealed a clear peak (r=0.96) at a load force phase lag of 10 ms. In the side-to-side case, a peak correlation between grip force (with low frequency drift removed) and load force (r=0.71) was observed at a grip force phase lag of 10 ms. In general, we observed persistent and tight coupling of grip force and load force with phase lags around zero for movement in either direction.

Although the frequencies of the up and down and side-to-side movements shown in Fig. 2 are similar (as indicated by inertial load modulation), the frequencies of load and grip force oscillation in the vertical movement are about half those in the side-to-side movement because gravity introduces an offset in load force in the latter.

In vertical movements, the amplitudes of load and inertial force modulation are equal whereas, in side-to-side movements, the extent of modulation of load force is less than that of inertial force (because gravitational and inertial forces act in orthogonal directions). One may ask whether, in general, fluctuations in grip force are more sensitive to variations in the total load force or the inertial force which acts in the direction of movement. In cyclical movements, it seems that the extent of grip force modulation depends on the amplitude of load force variations. While the amplitudes of inertial force modulation in the vertical and side-to-side movements shown in Fig. 2 are similar, the amplitudes of both grip and load force modulation are clearly less in the side-to-side movement.

In contrast, during point-to-point movements the amplitude of grip force modulation appears to be more closely linked to the amplitude of the modulation of vertical or horizontal force which is due to variation in inertial force. The modulations of grip force in the vertical and horizontal movements shown in Fig. 1 are similar in amplitude as are the modulations in inertial force. However, variation of load force (not shown in the figure) is substantially smaller in horizontal movements than in vertical movement.

At the end of the experiments described above, several subjects were provided with concurrent visual feedback of grip force and acceleration as time series waveforms on a monitor. All of them were surprised at the modulation in grip force. Given the strong coupling between grip and load force one may ask whether the coupling is open

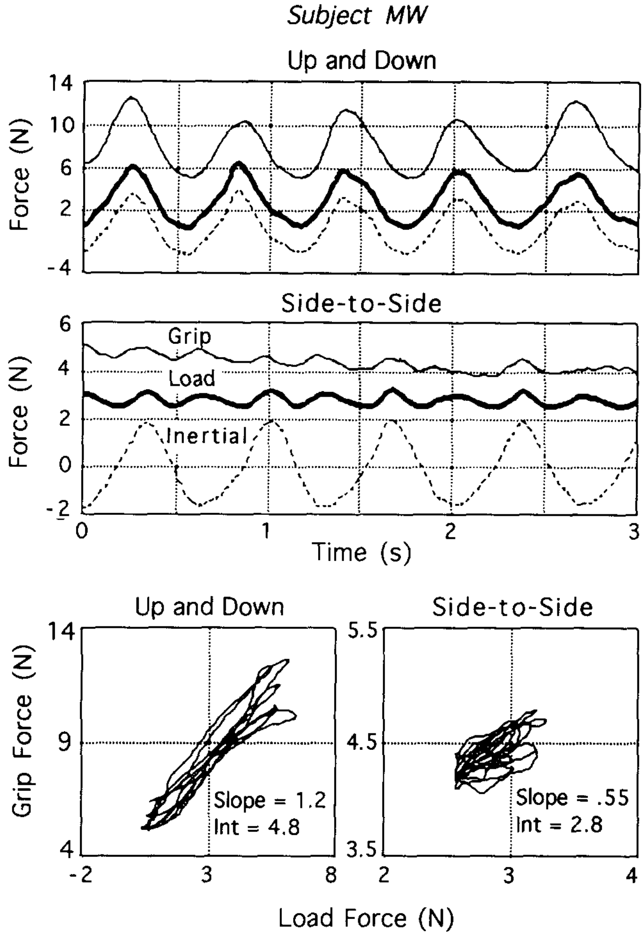

Fig. 2. Grip force modulation during cyclical movements. The subject (MW) made repetitive up-and-down (top) or side-to-side (middle) movements. In both directions, grip force (thin) is modulated in-phase with load force (thick). The inertial force, proportional to the acceleration of the object, is also shown (dashed). The stability and gain of the modulation is revealed in the graphs of grip force against load force (bottom panels). (Note that the low frequency drift that can be seen in grip force in the side-to-side movement example was removed by filtering before plotting grip versus load force.)

to voluntary influence or indeed whether subjects are able to suppress it. To explore this issue we carried out a preliminary test in which we asked subjects to produce cyclic up and down movement with the transducer while keeping grip force constant. Subjects were unable to keep grip force constant. Most subjects attempted to reduce grip force modulation by increasing the mean level of grip force well above the maximum grip force normally observed. This is a sensible strategy because increases in grip force during the movement would not then be required to prevent the object from slipping. Nevertheless, we found that grip force was still modulated in phase with acceleration although the amplitude of modulation was reduced.

Conclusion: In a series of elegant experiments, Johansson and Westling have established that there is a relation between grip force and load force in lifting and holding objects [4–6]. We show here that this coupling extends to voluntary movements where changes in load force are induced by arm movement. Johansson and Westling [4, 6] have shown that grip force increases during object lifting and that the rate of increase varies according to the object attributes (e.g., weight, surface texture). We have demonstrated that in simply moving an object (quite apart from picking it up) there are both increases and decreases in grip force and that these are exquisitely timed to coincide with changes in movement-induced load. We believe that this coupling is most likely very general and will hold for many different types of movement-induced loading. For example, we have seen grip force modulation when subjects rotate an object.

The question arises as to why grip force is modulated in phase with load force during movement when it might be simpler to raise the grip force to a steady level (sufficient to prevent slipping) for the duration of the movement. Johansson and Westling [4] have suggested that grip force scales with object weight in order to economize effort. Economy of effort might also provide an explanation for the covariance of grip and load force that we see during object movement. Another possibility is that grip force is modulated to improve the ability of the hand to sense changes in load force. With lower grip forces, the fingers will be more compliant allowing greater stimulation of motion-dependent sensors. In addition, the finger pads will be less compressed which might be expected to allow greater sensitivity in the sensory apparatus of the hand. Whatever the reasons for the linkage that we have described in this report, a major goal for future work will be the identification of the underlying neural pathways.

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