Exp Brain Res (1992) 89:172–180

Experimental Brain Research

Feedforward stabilization in a bimanual unloading task

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Received June 4, 1991 / Accepted November 5, 1991

Summary. When one hand removes a load from the other hand, feedforward motor commands stabilize the position of the unloaded hand. We studied the stabilization of the postural hand using a novel apparatus that allowed unloading at different rates, and unexpected uncoupling of the unloading force from the postural hand. Feedforward stabilization of hand position was observed in all subjects. This stabilization was achieved both by deactivation of postural agonist muscles and by activation of postural antagonist muscles. The neural feedforward command apparently increased with unloading rate. However, the command only partially canceled the interaction torque generated by removing the load, and stabilization became less effective as unloading rate increased.

Key words: Bimanual unloading – Anticipatory postural adjustments – Feedforward control – Human wrist

Introduction

Since body segments are mechanically coupled to each other, voluntary movements of one set of segments destabilize the posture of other segments. Stabilizing activity in postural muscles has been observed before, during and after voluntary movements. Postural muscle activity that precedes the voluntary movement and predicts the impending dynamical disturbance is called feedforward stabilization, and has been observed in several experiments (Gahery and Massion 1981; Lee et al. 1987; Brown and Frank 1987; Massion and Dufosse 1988; Friedli et al. 1988; Bouisset and Zattara 1990).

A simple and tractable experiment for exploring feedforward stabilization has been developed by J. Massion and his group in Marseilles (Paulignan et al. 1989). Subjects attempt to maintain posture in a preloaded arm as the load is removed with the opposite arm. Massion's group has demonstrated that stabilization is achieved by feedforward deactivation of the postural muscles that support the load.

Many researchers have investigated the origin of the feedforward stabilization in this unloading task. Forget and Lamarre (1990) found this stabilization present in a deafferented man, demonstrating the central origin of this stabilization. Furthermore, experiments by Dufosse et al. (1985) suggest that the deactivation in postural arm muscles is not a voluntary descending signal but is generated from an efference copy of the voluntary descending signal sent to the other arm. Feedforward deactivation was not present when subjects triggered the unloading by pressing a button, or when the experimenter performed the unloading after a warning tone. Yet the deactivation was present when subjects triggered unloading by lifting a weight with the other arm. There is evidence that the supplementary motor area plays a role in the generation of this efference copy: Massion et al. (1989) observed a lack of feedforward stabilization in patients with damaged supplementary motor areas.

The most detailed investigation of this unloading task has been reported by Paulignan et al. (1989). In their experiments, the load was suspended from the subject's right forearm and removed in a step-like fashion. The subject was instructed to maintain posture of the right arm as the unloading was triggered by activity in the left arm. Left arm trigger signals included threshold crossings in electromyogram (EMG), movement, and force. A brief period of decreased postural arm biceps EMG was observed when the subject triggered the unloading. This deactivation was more or less coincident with EMG rise in the subject's left arm and must therefore be feedforward. The deactivation was absent when the experimenter triggered the unloading. Once the coordination had been established with practice, the deactivation was independent of the weight lifted by the left arm: the same deactivation ocurred if the left arm lifted 0.5 kg, 1 kg, or 2 kg. This suggested that the deactivation might be a preprogrammed response, triggered by unloading arm activity but insensitive to its level. However, as

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Paulignan et al. (1989) point out, the use of an unloading apparatus which always removed the load with the same rate could have obscured the dependence of the feedforward stabilization on unloading arm activity.

Our aim was to study the dependence of the feedforward stabilization on the voluntary unloading signal, which we parameterized by the maximum rate of unloading. The apparatus we used allowed unloading at various rates. By separating the torques due to the unloading arm from those due to the postural arm, our apparatus also allowed us to trick the subject occasionally, leaving the load on the postural arm despite an unloading movement by the other arm. By this means we could measure kinematic, rather than electromyographic, consequences of the feedforward command.

Methods

Overview of experiments

Subjects sat upright in a chair with the right forearm resting on a table, and the right elbow at approximately ninety degrees. The right hand held up a load attached by a cable and pulley to a rigid handle. Subjects were instructed to keep the right hand as still as possible as the load was relieved. Each experimental trial consisted of a single unloading of the right hand, either by the subject or by the experimenter. The apparatus shown in Fig. 1 and described below was designed to separate the torques due to the two hands, and thus allow the forces applied by the left hand to be separated from the right hand.

Five subjects were tested. Three were highly practiced, and two had only enough practice to perform the experiment.

Each subject performed three sets of fifty trials. In the first two sets of trials, the subject removed a load from his right hand using his left hand. To guarantee a wide range of unloading rates, the experimenter viewed a display showing the peak unloading force rate for the trial just completed, and a histogram of peak unloading force rates for all the trials in the set. He then informed the subject of the peak unloading force rate of the trial just completed, and directed him to unload faster or slower, according to the contents of the histogram.

These "self"-unloadings were intermixed randomly with from six to ten trials in which the subject performed the unloading action with the left hand, but the load remained on the right hand. A special apparatus, described below, allowed the experimenter to unexpectedly uncouple the torques applied by the unloading (left) arm from the postural (right) hand by blocking the input to the motor. We will call these unexpectedly uncoupled movements "blocked" trials. We limited the number of blocked trials in order to minimize disturbance of the subject's normal self-unloading strategy. Many of the subjects rested during the two sets of self-unloadings to assure fatigue was not a factor.

After performing the two sets of "self" unloading trials, the subjects were allowed to rest, and then performed a third set of fifty trials. In the third set of trials, the experimenter performed the unloading action. As before, the subject was instructed to keep the right hand as still as possible. We call these unloadings by the experimenter "imposed" trials. The experimenter was careful to duplicate the subject's unloading arm technique in an attempt to guarantee similar force traces. Fifty of these "imposed" trials were recorded with a wide range of unloading rates.

Apparatus

The apparatus, shown in Fig. 1, simulates natural unloading. A 1 kg weight suspended over the back of the table is attached to a load plate which applies a torque (1.3 Nm) about the right wrist. An equal weight applies a force to a second load plate via a cable passing through the plate and connected to a force transducer. Each load plate is free to rotate about an axis through the table (the shaft of an electric motor attached to the bottom of table). The subject lifts the left weight by pulling on a cord connected to the force transducer, displacing the transducer off of the left load plate. The force in the transducer is measured, scaled appropriately, and used as a command signal to the torque motor under the right hand. The torque motor acts on the load plate to unload the postural arm, thus simulating natural unloading.

This simulated unloading allows the experimenter to unexpectedly uncouple the torques applied by the unloading arm from the postural wrist by blocking the input to the motor. For such "blocked" trials, any torques applied to the postural wrist arise solely from the feedforward stabilizing command. Thus the ap-

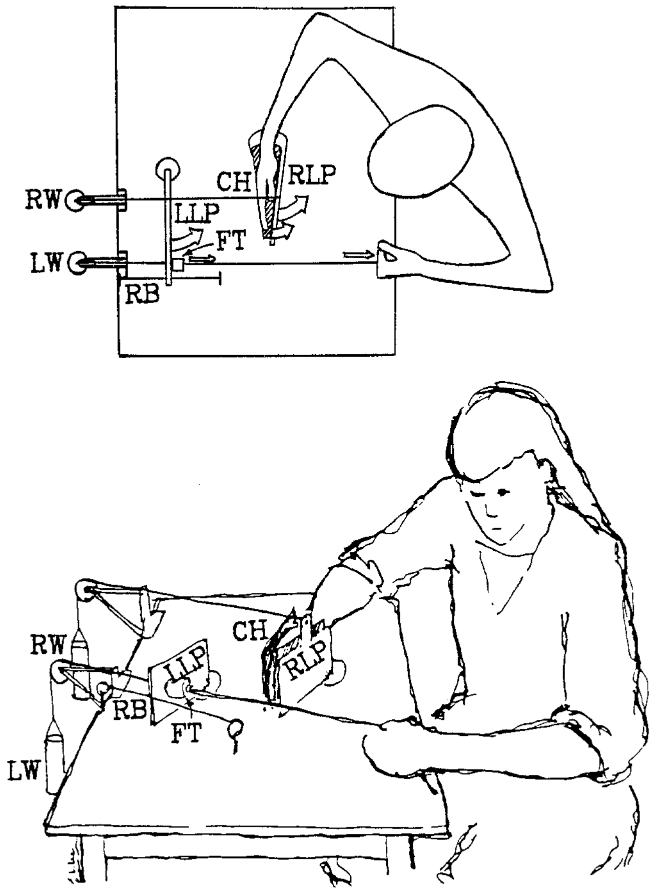

Fig. 1. Experimental apparatus for simulating bimanual load lifting, shown from two views. A 1 kg weight (RW) suspended over the back of the table pulls on a load plate (RLP) which applies a torque about the subject's right wrist. The right wrist is held by a light weight cardboard handle (CH) which is free to extend away from the right load plate. The subject unloads the right hand with the left hand by lifting a matched weight (LW) supported by a second load plate (LLP). A force transducer (FT) measures the force produced by the left arm and feeds it back to a motor under the right hand, which produces a torque to lift the right hand weight. The cable connecting the left hand to the left weight passes through a hole in the left load plate. When the subject is not lifting the left weight, the force transducer rests against the left load plate, and rubber bands (RB) support the left load plate/force transducer/left weight system. When the subject lifts the left weight, the force transducer is pulled away from the left load plate, and the rubber bands simulate the compliance of the right hand

paratus effectively isolates the effects of the feedforward stabilizing command.

The left load plate/weight/transducer system is made dynamically similar to the right hand/load plate/weight system by use of equal weights at equal moment arms and similar load plates. Rubber bands attached to the end of the left load plate simulate the stiffness of the right wrist (10–20 Nm/rad, Lehman and Calhoun 1990). The impedance seen by the unloading arm is thus very close to the impedance seen by the torque motor.

To test the apparatus, one subject also performed "natural" unloading, for which the motor was turned off and the transducer was attached directly to the load plate. Either the subject or the experimenter pulled on the transducer, generating "natural self" and "natural imposed" trials.

The right wrist is free to flex or extend, and is held only by a light weight cardboard handle against which the right load plate presses. The angle of the right wrist with respect to the table is measured by subtracting the output of a potentiometer which measures the angle of the cardboard handle with respect to the load plate from the output of a second potentiometer which measures the angle of the load plate with respect to the table.

Data collection and analysis

Force transducer and potentiometer traces were sampled at 500 HZ and stored on an IBM PC. Hand velocity and acceleration traces were obtained by digitally differentiating the position traces (Lancos differentiating filter, Hamming 1983). The force transducer traces were digitally differentiated to generate force rate traces.

Electromyograms from one practiced and one unpracticed subject were also recorded. Eight mm Ag/AgCl surface electrodes recorded the electrical activity of the flexor carpi radialis and extensor carpi radialis. Three unloading rates (measured by maximum force rate) that spanned the subject's range of unloading were chosen and twenty "self" and twenty "imposed" trials were taken at each of these maximum unloading rates. EMGs were bandpass filtered, sampled at 500 Hz, synchronized at the time of peak force rate, rectified, and averaged.

Results

Subjects stabilize the postural hand more effectively when they perform the unloading than when the experimenter does. Typical "self", "imposed", and "blocked" trials, selected for similar unloading force traces, are contrasted in Fig. 2. The "self" hand displacement is much less than the "imposed" hand displacement. The mechanism for this stabilization is a *feedforward* motor command – the postural arm compensates for the unloading command, rather than for the disturbance created by the unloading command. The compensation occurs even in the absence of an unloading torque: in the "blocked" trial, the hand moves backwards. Movement during the "blocked" trial also shows that the feedforward command does not simply stiffen the wrist.

We chose the first peak of postural wrist acceleration to parameterize the effects of the feedforward stabilization. The first peak of hand acceleration is well-defined for "self", "imposed" and "blocked" trials (e.g., Fig. 2). It occurs before feedback signals influence the acceleration: for all but the slowest unloading rates, the delay from unloading onset to peak acceleration was less than

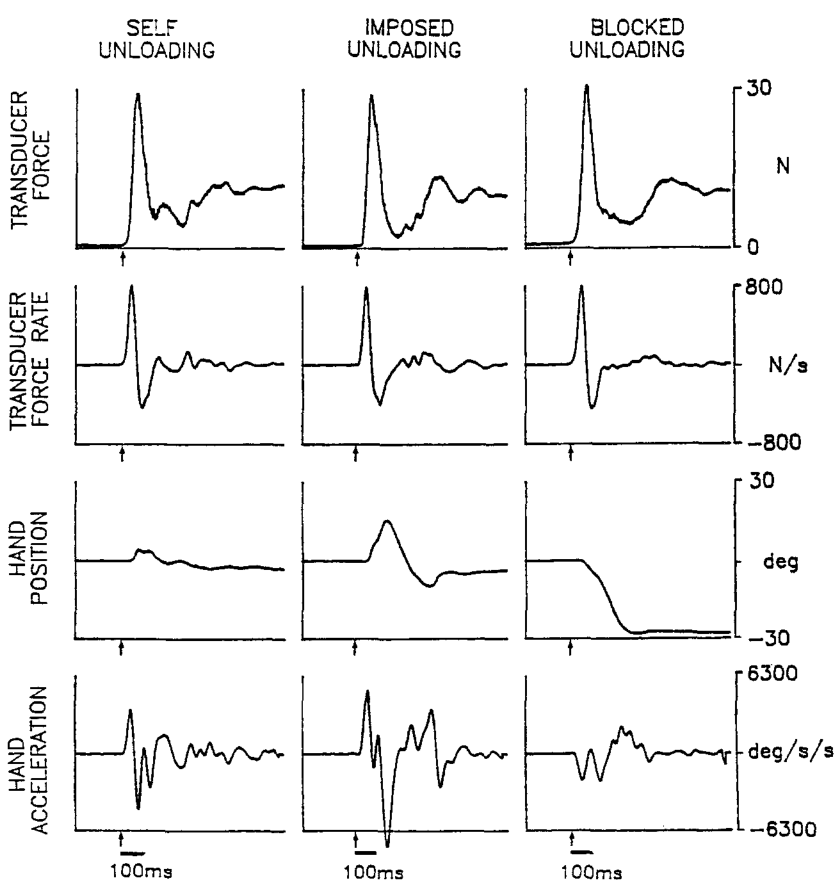

Fig. 2. Force and rate of change of force for the left hand, and position and acceleration of the right hand for single "self" "imposed" and "blocked" trials. Arrows indicate first change in force

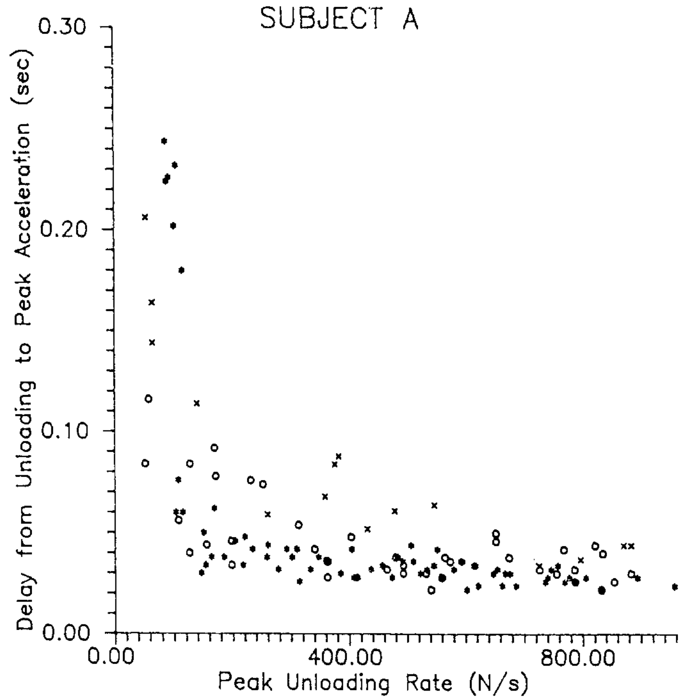

Fig. 3. Delay from initiation of left hand unloading (first change in force) to peak angular acceleration of right hand as a function of peak unloading rate. * "self"; ○ "imposed"; x "blocked"

100 ms (Fig. 3). The first changes in EMG in "imposed" trials occurred from 65–80 ms after initiation of unloading. At this latency we observed a stretch reflex in the postural antagonist muscles and an unloading reflex in the postural agonist muscles (the unloading reflex is the feedback deactivation of muscles supporting a load when that load is removed (Angel et al. 1965; Struppler et al. 1973)). We also measured a 35 ms delay from EMG to force. The first peak in hand acceleration is therefore not corrupted by reflexes and can be used as an indicator of feedforward influences. Root mean square (RMS) hand position, averaged over the first 100 ms after unloading, was also used to quantify feedforward influences. RMS position can be interpreted as average position error.

We measured feedforward stabilization over a wide range of unloading rates for "natural" unloading by one practiced subject (Fig. 4). For "natural" unloading the force transducer was attached directly to the load plate and the unloading force acted directly on the load plate. The subject was able to decrease peak hand acceleration and RMS position error in "self" unloading compared to "imposed" unloading, at any given peak unloading rate. The variability in "self" unloadings was greater than that in "imposed" unloadings. Even though the peak hand accelerations are smaller for the "self" trials than for the "imposed" trials, the hand still accelerates during the self trials. Thus the feedforward stabilization only partially cancels the unloading torque. The compensation, measured either by peak acceleration or RMS position, is less effective at faster unloading rates.

When the motor was used to simulate unloading, all subjects showed feedforward stabilization similar to that seen in the "natural" unloading for subject B (compare

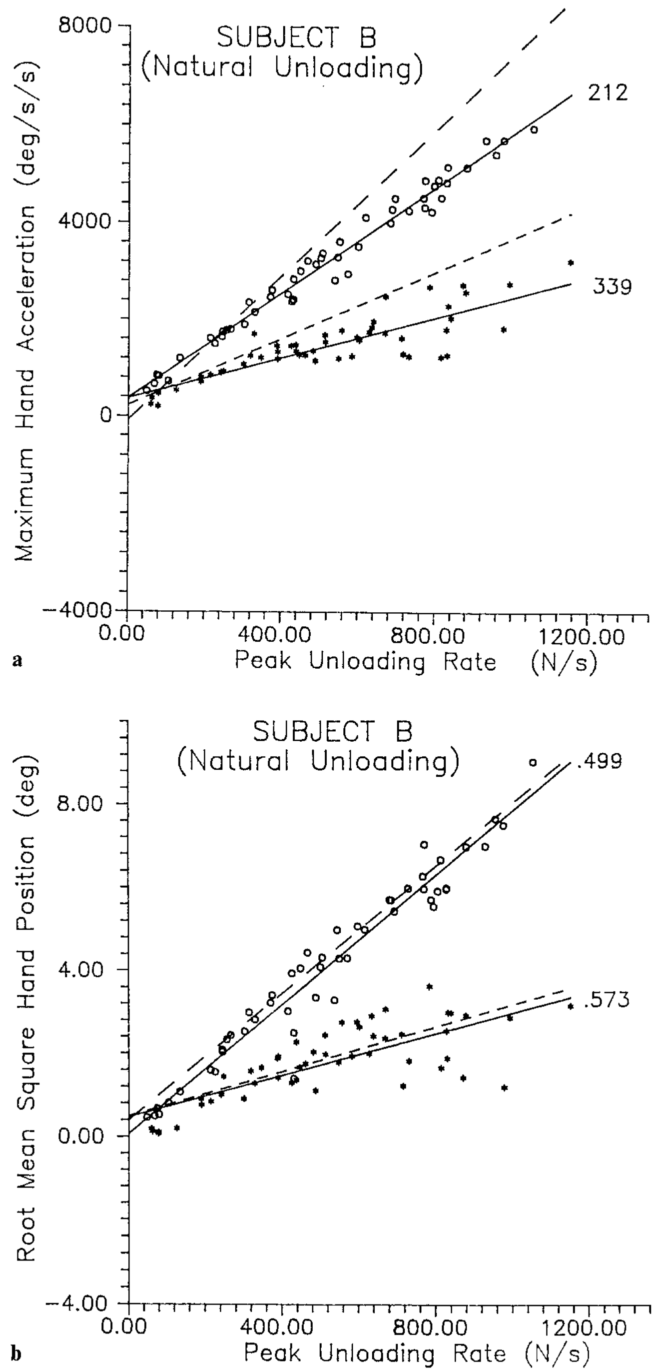

Fig. 4. a Maximum angular acceleration of right hand versus peak unloading rate for "natural" unloading (left hand pulls on the right hand plate). Linear regressions are plotted for "natural imposed" (○) and "natural self" (*) trials. Root mean square error about the regression line is indicated next to each line. Linear regressions for subject B "imposed" (long dashes) and "self" (short dashes) are also plotted. **b** Root mean square right hand angle (over first 100 ms) as a function of peak unloading rate for the same subject

Figs. 5 and 6 with Fig. 4) – peak hand accelerations (Fig. 5) and RMS positions (Fig. 6) were smaller for the "self" trials than for the "imposed" trials; the spread of the "self" trials was greater than the spread of the "imposed" trials; the compensation was imperfect, becoming less effective at faster unloading rates. The simulation of

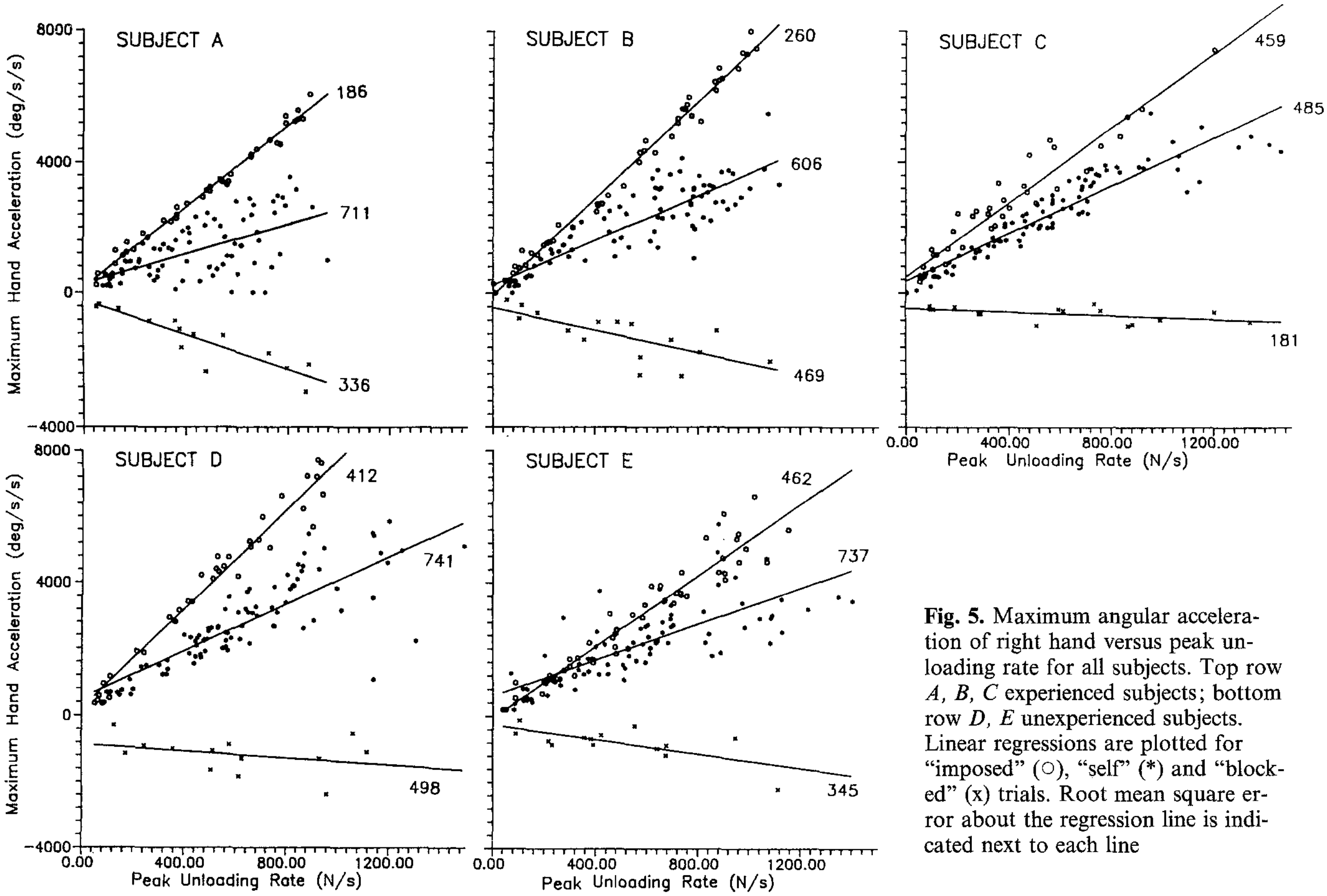

Fig. 5. Maximum angular acceleration of right hand versus peak unloading rate for all subjects. Top row *A, B, C* experienced subjects; bottom row *D, E* unexperienced subjects. Linear regressions are plotted for "imposed" (○), "self" (*) and "blocked" (x) trials. Root mean square error about the regression line is indicated next to each line

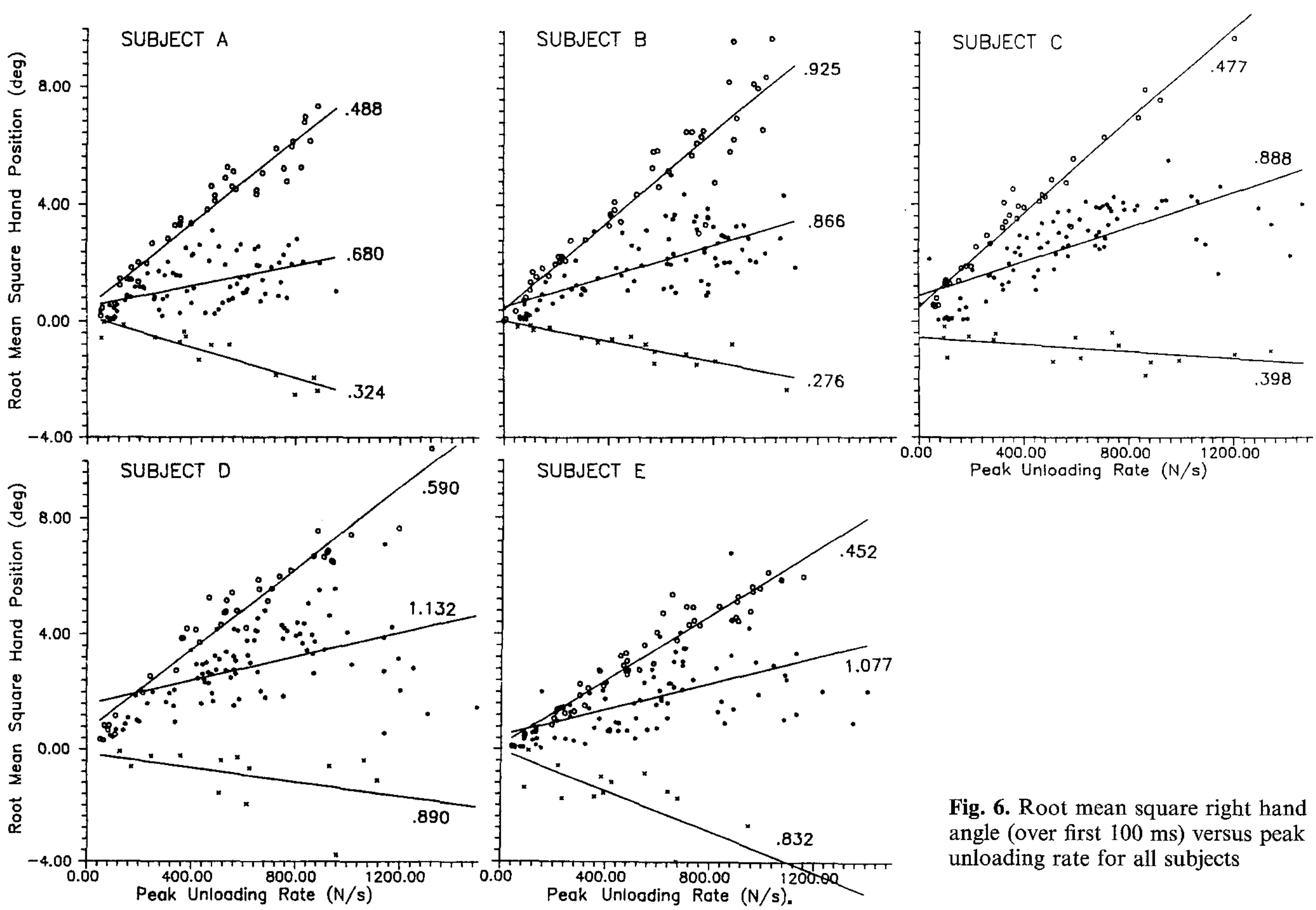

Fig. 6. Root mean square right hand angle (over first 100 ms) versus peak unloading rate for all subjects

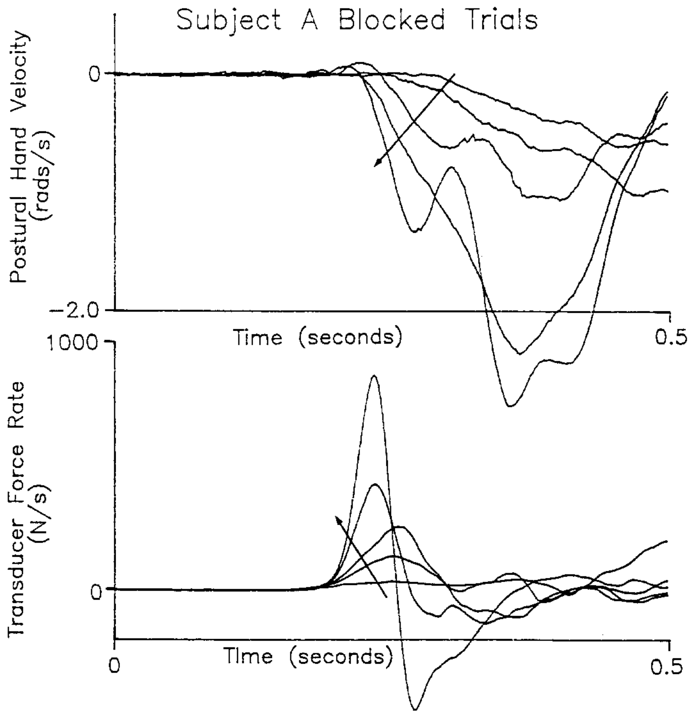

Fig. 7. Postural hand angular velocities (top) for blocked trials "unloaded" at different rates (bottom). Trials are synchronized on rise in unloading force

unloading gave us access to kinematic, rather than electromyographic, effects of the feedforward stabilization command – postural hand kinematics during "blocked" trials. These showed that the feedforward command increases with unloading rate.

Closer examination of the kinematics of the "blocked" trials emphasizes this increase in the feedforward command with unloading rate (Fig. 7). Postural hand acceleration increases with force rate of the "unloading" arm from the very beginning of the postural hand movement.

The apparatus adequately simulates the main features of the "natural" unloading process as evidenced by the qualitative similarity between Fig. 4 and Figs. 5 and 6. Quantitatively, however, the regression line slopes for peak accelerations in "self" and "natural self" trials are significantly different, as are the slopes for "imposed" and "natural imposed" trials (Fig. 4A). These differences in slope are probably due to differences between the dynamics of the "artificial wrist" and the subject's own wrist. The quality of simulation appears better when measured by RMS hand position. The slopes for subject B's RMS hand position in the "imposed" and "natural imposed" are not significantly different, nor are the slopes for RMS hand position in the "self" and "natural self" trials (Fig. 4B). Differences in acceleration peaks

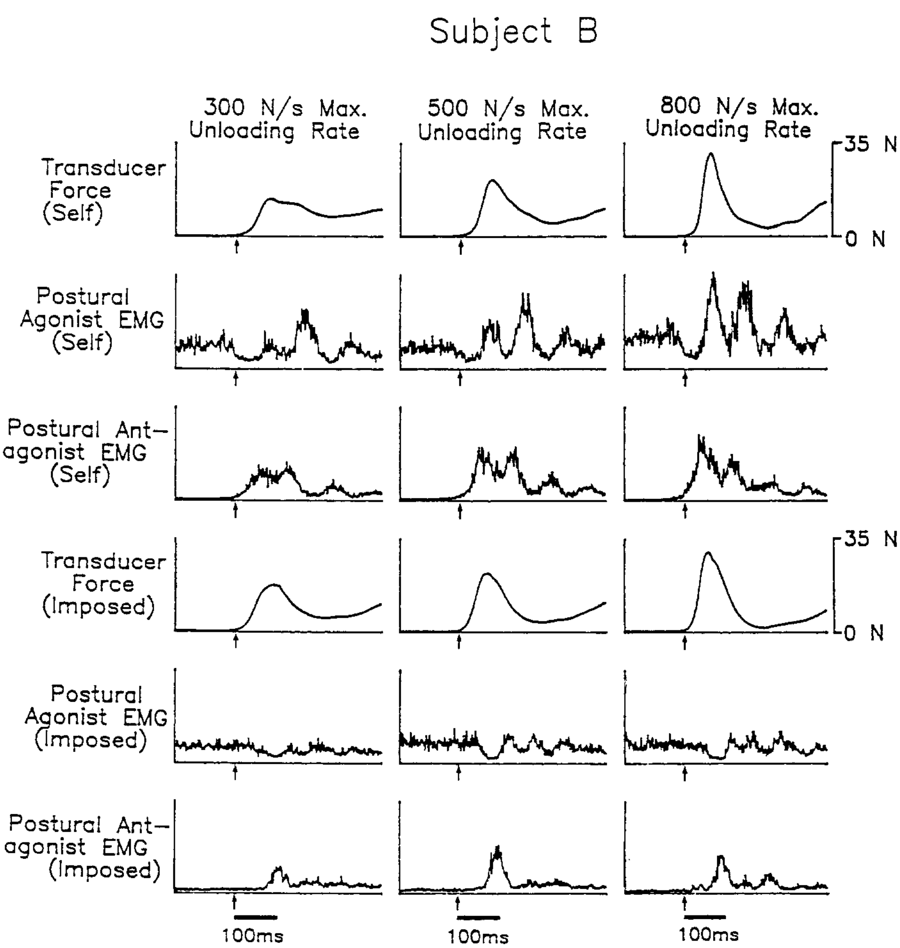

Fig. 8. Force and postural arm EMG for "self" and "imposed" unloadings at three different rates (columns). Arrows indicate initiation of unloading. All traces are 20 trial averages taken from an experienced subject

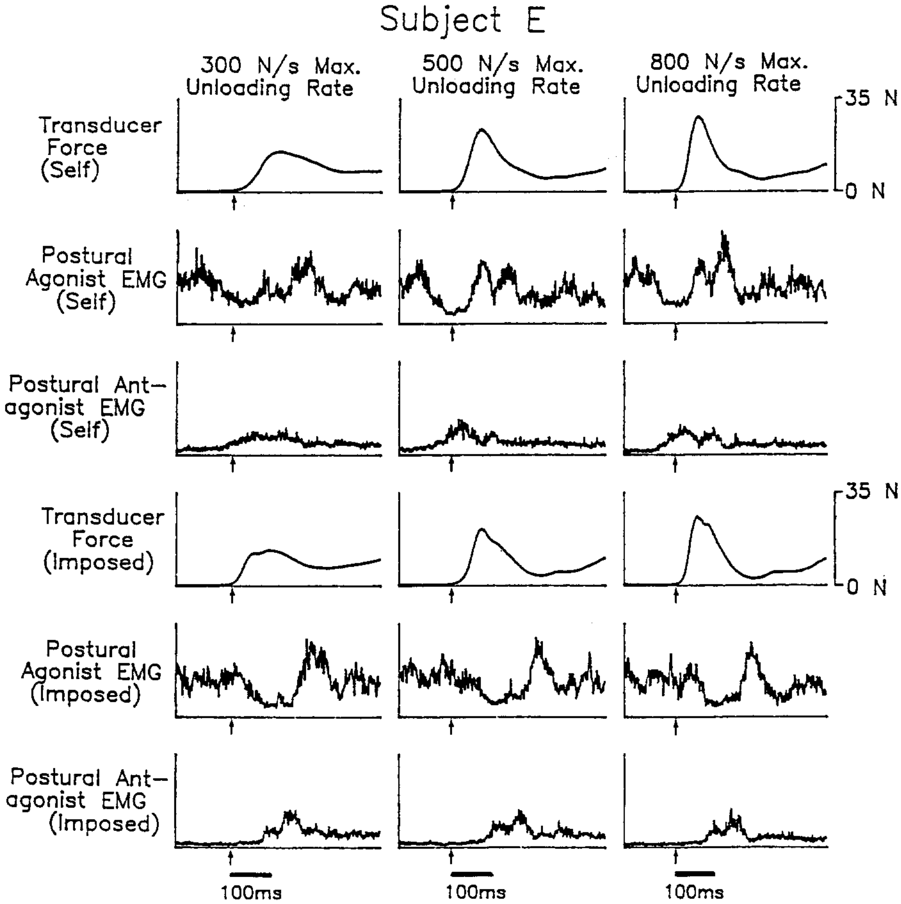

Fig. 9. Force and postural arm EMG at different rates for an inexperienced subject

may be obscured by equal differences in deceleration valleys, integrating to the same RMS positions.

One other difference between the simulated unloadings and the natural unloadings is a smaller spread in the "natural self" trials versus the "self" trials (compare Fig. 4A and subject B in Fig. 5). The smaller spread might be attributed to the intermixing of "blocked" trials with "self" trials. "Blocked" trials are disconcerting to the subject because the subject's hand moves backwards unexpectedly. Subjects may have altered the feedforward command in anticipation of more blocked trials. Attempts were made to stabilize feedforward performance after each blocked trial with 5–10 practice unloadings. Nevertheless, it is possible that the disconcerting effects of "blocked" trials contributed to "self" trial spread.

Electromyograms from an experienced subject show that the feedforward stabilization occurs by deactivating postural agonists and activating postural antagonists (Fig. 8). The first drop in flexor EMG in the "self" trials occurs more or less simultaneously with the rise in unloading force, thus showing the feedforward origin of this deactivation. Simultaneous with this deactivation is feedforward activation of the postural antagonist. Changes in the sizes and shapes of the feedforward commands are difficult to quantify from these averages. Notice that the EMGs from the "imposed" unloading show no change until about 70 ms after rise in force, and thus have no feedforward component. At 70 ms, the unloading reflex is seen in the postural agonist muscle and a stretch reflex in the postural antagonist muscle.

The feedforward commands to postural agonist and antagonist muscles are also apparent in the "self" trials and absent from the "imposed" trials in EMG's from an inexperienced subject (Fig. 9). However, the onset of feedforward commands relative to unloading onset varies from -17 ms for the slowest speed to about -40 ms at the fastest speed: i.e. the EMG changes precede unloading.

Discussion

In summary, we have the following results. Feedforward stabilization of postural muscles in "self" unloading is observed in all subjects, and at all unloading rates, during simulated unloading. This stabilization is achieved by a deactivation of postural agonist muscles and an activation of postural antagonist muscles. The feedforward command apparently increases with unloading rate. However, the command only partially cancels the interaction torque generated by removing the load. As unloading rate increases, the stabilization becomes less effective.

One strategy for generating feedforward commands would be to use preprogrammed stabilizing commands, independent of the unloading rate and triggered by some

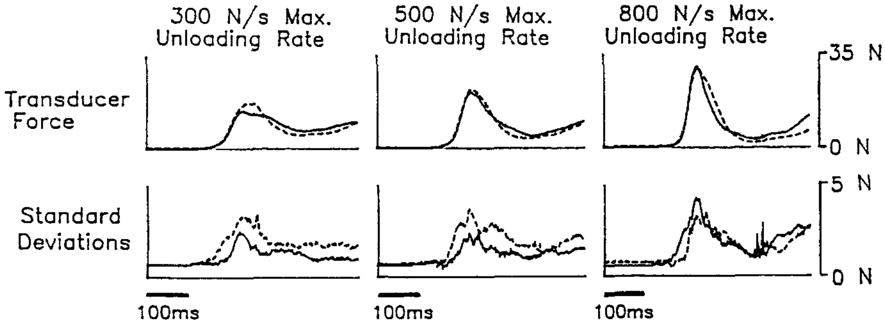

Fig. 10. Average force traces for three peak unloading rates (columns) for "self" (solid) and "imposed" (dashed) trials. The second row plots standard deviations of the force averages

threshold of activity in the unloading arm. The results of Paulignan et al. (1989) suggest such a strategy. In our experiment, such a strategy would result in two populations for the "blocked" trials: one population for which unloading arm activity crossed the threshold, and one population for which it did not. The steady increase in "blocked" hand acceleration for faster unloading rates argue against this strategy and suggests the magnitude of the feedforward command increases with unloading rate. Grading of postural muscle activity with rate of voluntary movement similar to our findings was reported by Lee et al. (1987), who studied postural muscle EMG responses to voluntary arm movements.

EMG recordings indicated that the feedforward stabilization is achieved by deactivating the postural agonist and activating the postural antagonist (Figs. 8 and 9). Thus stabilization is achieved by cancellation of interaction torques rather than by stiffening the wrist. Feedforward activation of the postural antagonist was also observed by Forget et al. (1990) but not by Paulignan et al. (1989).

The fact that the postural hand accelerates during "self" unloading implies that feedforward stabilization only partially cancels the interaction torque generated during unloading. Stabilization may be only approximate because of limitations in the neuromuscular hardware that implements the stabilization. On the other hand, more precise stabilization may not be necessary.

The stabilization is not only imperfect, but also noisy. The variability in the stabilization is probably not in the postural arm dynamics, muscles, or the tonic postural signal, because the standard deviation in "self" trials is always greater than that in "imposed" trials, for which the signal to the postural arm doesn't change (up to reflex time). It is also unlikely that the noise is in the unloading arm or the voluntary unloading signal, because the experimenter and the subject show about the same variability in their unloading trajectories (Fig. 10). The noise is therefore likely to be in the transformation from voluntary unloading signal to the feedforward postural adjustment signal.

Given the lack of an obvious cost of an error, it is perhaps surprising that the stabilization is as good as it is. We hypothesize two other possible uses for this coordination. First, the coordination may be used to simplify control when a person manipulates an object with his hands. Suppose an object is supported by the postural arm and the person wishes to remove this object with a desired trajectory from the support. Due to the spring-like nature of muscles and tendons, there will be a period early in the unloading when both the postural and unloading arms are exerting forces on the object. The central nervous system (CNS) must coordinate the voluntary unloading signal with the force the postural arm places on the object during this coupled phase. If however, the CNS can counteract the spring-like nature of the postural arm with feedforward stabilization, the coupling time is reduced and the postural arm mimics a grounded surface. Then the CNS can use the same unloading signal as it uses to lift the object off any grounded surface. This is analogous to the dynamic simplifications in moving the arm about in the workspace with the shoulder joint stabilized by feedforward signals.

The second possible use of the coordination is that it may permit a person who is grasping an object with two hands to vary grasp force while keeping the object stationary. A two-hand grasp controller could thus make use of the observed feedforward stabilization in order to uncouple grasp force control from grasp motion control. If the observed coordination is used for this purpose, the distinction between voluntary and postural signals becomes blurred: during two-hand grasp, either or both hands may be controlled voluntarily. Future research should explore whether the observed bimanual coordination is used to control grasp, and/or to simplify control during bimanual manipulation.

Acknowledgements. The authors would like to thank Mike Miller, Mark Lovich, and Bennet Yang for their contributions through L. Stark's class ME 210, and Laurie Lee for her artistic contributions. P.S.L. was supported by a UCSF President's Health Science fellowship. D.J.R. was supported by a NSF graduate fellowship.

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