Task Dependent Patterns of Muscle Activation at the Shoulder and Elbow for Unconstrained Arm Movements

DI-AN HONG, DANIEL M. CORCOS, AND GERALD L. GOTTLIEB
Departments of Physiology and Neurological Sciences, Rush Medical College, Chicago 60612, and School of Kinesiology, University of Illinois at Chicago, Chicago, Illinois 60680

SUMMARY AND CONCLUSIONS

1. Six subjects performed three series of pointing tasks with the unconstrained arm. Series one and two required subjects to move as fast as possible with different weights attached to the wrist. The first required flexion at both shoulder and elbow joints. The second required shoulder flexion and elbow extension. The third series required flexion at both joints and subjects were intentionally instructed to vary movement speed. These three pointing tasks were selected as the simplest progression from single to multiple degree of freedom movements in which different patterns of motoneuron excitation are required depending on whether movements are made against different loads or at different intended speeds.

2. Changes in load and changes in intended speed both produced systematic but different changes in the patterns of muscle activity and joint torque in both the elbow and shoulder muscles. These patterns are the same found during constrained, single-joint elbow flexion movements. The changes are expressed in the rates of rise, durations, and latencies of the electromyographic (EMG) bursts and in the rates of rise of torque that have specific dependencies based on the force requirements of the task.

3. A consistent, almost linear relationship is observed between muscle torque at the shoulder and at the elbow for all three tasks. Similar systematic changes were not seen in the kinematic description of joint angles.

4. The systematic relationship between torque and EMG as well as between muscle torque at the shoulder and at the elbow across the different tasks is consistent with our hypothesis that movement planning and control can best be described in terms of the force requirements of the task. This hypothesis, developed for single joint movements, may be extended to the individual joints during movements of the entire limb.

INTRODUCTION

Previous work on how single-joint movements are controlled has suggested that pulses of motoneuron excitation are programmed based upon specific requirements of the intended movement task (Gottlieb et al. 1989). These task requirements can be conceptualized in terms of the forces required to move different distances, speeds and loads (Hoffman and Strick 1993). Motoneuron excitation patterns are generated by specifying the parameters of motoneuron pool excitation pulses, that is, their heights, widths, and agonist-antagonist timing, and lead to muscle contraction and force development (Gottlieb 1993). The movement trajectory is an emergent property of the muscle-load dynamics. This paper describes a series of experiments involving pointing movements of the arm to targets that were positioned to require shoulder flexion and either flexion or extension at the elbow. Previous studies have suggested that there are commonalities between the control of single degree of freedom and multiple degree of freedom movements (Lacquaniti et al. 1986; Wadman et al. 1980). The present experiments were designed to explore the extent to which these commonalities can be identified as different patterns of motoneuron pool excitation that depend on the force requirements of the task.

METHODS

Subjects

Six normal male human volunteers performed unrestrained pointing movements with their right arms. Each subject faced a small target (a cotton ball, 2 cm in diameter) positioned so that the movement was performed in a sagittal plane.

Tasks

For all tasks, the subjects stood at ease on an AMTI force platform. The first two tasks used one of four different inertial loads (0, 0.9, 2.2, and 3.12 kg, respectively) attached to the wrist. The first "load" task was initiated from a relaxed, standard posture: the arms hanging easily at the sides, palms facing the body. Movements to the target required about 30° of both shoulder and elbow flexion. The second load task was initiated from a different posture in which the forearm was flexed ~30° from full extension and the upper arm remained vertical. Each of the same four inertial loads was attached to the wrist. Movement to the target required ~40° of shoulder flexion and 10° of elbow extension. The third or "speed" task was initiated from the same posture to the same target as the first task at four different speeds with the 0.9 kg weight attached to the wrist.

Tasks 1 and 3, requiring flexion at both elbow and shoulder, were considered the simplest possible extrapolation from the single joint elbow flexions we have previously studied to a multijoint arm movement. They are, therefore, most likely to show control strategies that are similar to the single joint case. Task two required similar shoulder flexion accompanied by elbow extension that could be produced without the use of the elbow extensor muscles. Interaction torques, at least in principle, would be sufficient. It was chosen as one (of many possible) simple kinematic tasks likely to reveal different control strategies if they are used.

No detailed instructions were given about the hand path. Subjects were told to move as fast as possible for the two load tasks. For the speed task, the instructions were "move as fast as you can," "move fast but at your maximal speed," "move at a comfortable speed," and "move slowly." On a verbal get ready...
FIG. 1. Averaged arm movements for 3 tasks—A: with 4 different inertial loads, B: with the same 4 inertial loads from a different initial position from A, C: with 4 different speed instructions using a single inertial load and the same endpoints as part A. In all 3 parts of the Fig., the value of muscle torque at $t = 0$ was set to zero as were the EMGs in part B. EMGs were smoothed by a 45-ms rectangular window.
signal, subjects positioned their arm at the starting position until the experimenter said go. Subjects touched the soft target and stayed there until they heard a computer generated tone. Each subject performed 10 trials for each load or speed.

**Recording system**

A three-dimensional, electro-optical motion measurement system (OPTOTRACK 3010) recorded the locations of four markers attached to the shoulder, elbow, wrist, and index finger tip. EMG surface electrodes were taped over the bellies of the biceps brachii, triceps (lateral head), anterior, and posterior deltoid. The EMG signals were amplified, full-wave rectified, and low-pass filtered (100 Hz Paynter filter) (Gottlieb and Agarwal 1970). All signals were sampled at 200/s.

**Equations of motion**

A simplified model of the kinematic linkage of the human arm, which includes sagittal plane shoulder, elbow, and wrist joint rotations was used. Joint angles and their derivatives were calculated from the measured coordinate data of the distal and proximal segment endpoints. Muscle torques were computed by Newtonian equations of motion (Schneider et al. 1989) as the sum of the measured positional (gravitational) and calculated motion dependent components. These represent the net torque about each joint produced by the muscles. To perform these calculations, the inertial parameters of upper arm, forearm, and hand (mass, location of mass center, and principal moment of inertia) were estimated using statistical data (Winter 1979) and measurements of whole-body weight and limb lengths of each subject. Each additional weight attached to the wrist was assumed to be a point-mass located at the joint center of the wrist.

**RESULTS**

We illustrate our findings for the three tasks with representative data from one subject in Fig. 1. The movements in Fig. 1, A and B were aligned to the onset of the biceps EMG burst before averaging. In Fig. 1C, alignment was based on the initial rise of the AMTI vertical force component. Note that for the two load tasks in Fig. 1, A and B, muscle torques at both joints initially rise at load independent rates while for the speed task shown in Fig. 1C, the torques initially rise at speed dependent rates. Similar statements may be made about all the agonists muscle EMG bursts at both joints. The agonist bursts rise for longer times and have longer durations with increased loads. Their durations do not appear to be strongly sensitive to movement speed in Fig. 1C. The shoulder antagonist bursts are delayed by added loads (Fig. 1, A and B) or reduced speeds (Fig. 1C). The same EMG patterns are found for single-joint elbow flexion movements during similar tasks.

There is greater variability in the modulation of the elbow antagonist. In Fig. 1A burst onset is at a constant latency following the agonist, while burst area increases with load. Activation of the triceps in Fig. 1B is more like the single-joint pattern with a constant latency early component and a later component with a load dependent latency. In Fig. 1C the triceps pattern varies with speed in a manner similar to that of the posterior deltoid but to a lesser degree.

The coordination of the joints at the initiation of a movement is illustrated by Fig. 2. A–C correspond to the same three tasks in Fig. 1. The top two sections show elbow/shoulder angle and elbow/shoulder torque for the first 400 ms of data in Fig. 1. The data have been aligned at t = 0 to the same values to illustrate the initial changes in the variables. The bottom section shows the motion in Cartesian space with different sized symbols bounding the first 400 ms. In Cartesian space, the paths are not sensitive to either load or speed but in joint angle space there is greater dispersion, especially for task 2. The changes in torque at the two joints remain in almost constant proportion throughout the initial rise for all three tasks, irrespective of the load or the intended speed.

**DISCUSSION**

Multiple degree of freedom movements pose at least three challenges to the central nervous system that are not present in single degree of freedom tasks: kinematic redundancy allows more than one path to a target, muscle redundancy allows many combinations of synergistic and antagonistic muscles including two joint muscles to generate the same trajectory, and complex dynamical interactions may occur between limb segments. All three factors were present in the tasks described here. Although only motions at the shoulder and elbow are illustrated, there were no external constraints to translation of the shoulder or rotation of the wrist.

The consistency of the Cartesian path provides the basis for arguments in favor of trajectory planning. This requires the controller to automatically compensate for added loads (Lacquaniti et al. 1982). Instead, we suggest that the data are consistent with a model, developed for single joint movements, that plans movements in terms of the specific force requirements of the task. The outputs of this plan are rectangular muscle excitation pulses. Pulse width and antagonist latency are proportionally scaled to the load while height and the reciprocal of the antagonist latency are proportionally scaled to the intended speed (Gottlieb 1993). This conclusion is based on the similarity between the EMG and muscle torque profiles in all three of the tasks we have used and the linear relationship between the shoulder and elbow torques. The patterns of torque modulation and of three of the four EMGs (agonists anterior deltoid and biceps and antagonist posterior deltoid) (Fig. 1, A and B) are typical of the findings for single degree of freedom, inertially loaded movements when the inertial load increases (Gottlieb et al. 1989). The patterns of torque and EMG modulation in Fig. 1C are also typical of single joint movements when speed in intentionally varied (Corcos et al. 1989).

Our findings for different speeds are consistent with those reported by Flanders and Herrmann (1992). However they found EMG burst duration to scale with movement time. The reasons for the different findings are not clear. The speed-independence of burst duration here is identical to

---

2 Our use here of the term "agonist" is equivalent to "flexor" (biceps and anterior deltoid) for all these movements. In describing the interacting motions of multiple limb segments, agonist does not have a clear and unambiguous definition (Karsd and Hasan 1991). The term does indicate the muscle that acts in the direction of the initial rise of joint torque, regardless of the direction in which the joint initially rotates. Whether this is in fact an adequate general definition of agonist requires further study.
FIG. 2. The paths of the 3 movements shown in Fig. 1, represented in joint angle space (top), joint torque space (middle) and Cartesian space (bottom). Circles drawn on the Cartesian paths correspond to the location of the finger tip at \( t = 400 \) ms in Fig. 1. Only the first 400 ms is plotted in angle and torque space. The circle diameters are proportional to inertial load (A and B) or inverse movement speed (C).
the single-joint findings of Gottlieb et al. (1989) and Hoffman and Strick (1993). Although there are probably situations in which duration changes, the degree of change under different loads is significantly greater than that produced by deliberate changes in speed.

Several commentaries to Gottlieb et al. (1989) questioned whether the study of single degree of freedom movements would shed light on the study of more complex, multiple degree of freedom movements. We have shown here that not only are the patterns of torque and EMG during multiple degree of freedom movements similar to those of single degree of freedom movements (Lacquaniti et al. 1986) but their dependence upon specific features of the movement task such as load and speed are also similar. Given the infinite number of variations on movement distance and direction that can be accomplished by multijoint limb movements (Karst and Hasan 1991; Wadman et al. 1980), it is clear that we have only begun to examine the generalizability of single joint control strategies to multijoint tasks. These limited results support and extend the proposition suggested by Wadman et al. (1980) that "simple" control principles exist that help solve complex dynamical problems. We conclude that organizing principles based on joint torque requirements of the task and derived from the study of single-degree of freedom movements may be extendable to the understanding of multi-degree of freedom movements.

We thank K. Lee and S. Jackson for technical assistance and Z. Hasan for insightful comments.

This work was supported in part by NIH Grants NS-01508, NS-28127, NS-28176, and AR-33189.

Address for reprint requests: D. M. Corcos, School of Kinesiology (M/C 194), University of Illinois at Chicago, 901 West Roosevelt Road, Chicago, IL 60680.

Received 6 October 1993; accepted in final form 9 December 1993.

REFERENCES


