

Control of the Wrist in Three-Joint Arm Movements to Multiple Directions in the Horizontal Plane

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Koshland, Gail F., James C. Galloway, and Cedrine J. Nevoret-Bell. Control of the wrist in three-joint arm movements to multiple directions in the horizontal plane. *J. Neurophysiol.* 83: 3188–3195, 2000. In a reaching movement, the wrist joint is subject to inertial effects from proximal joint motion. However, precise control of the wrist is important for reaching accuracy. Studies of three-joint arm movements report that the wrist joint moves little during point-to-point reaches, but muscle activities and kinetics have not yet been described across a range of movement directions. We hypothesized that to minimize wrist motion, muscle torques at the wrist must perfectly counteract inertial effects arising from proximal joint motion. Subjects were given no instructions regarding joint movement and were observed to keep the wrist nearly motionless during center-out reaches to directions throughout the horizontal plane. Consistent with this, wrist muscle torques exactly mirrored interaction torques, in contrast to muscle torques at proximal joints. These findings suggest that in this reaching task the nervous system chooses to minimize wrist motion by anticipating dynamic inertial effects. The wrist muscle torques were associated with a direction-dependent choice of muscles, also characterized by initial reciprocal activation rather than initial coactivation to stiffen the wrist joint. In a second experiment, the same pattern of muscle activities persisted even after many trials reaching with the wrist joint immobilized. These results, combined with similar features at the three joints, such as cosine-like tuning of muscle torques and of muscle onsets across direction, suggest that the nervous system uses similar rules for muscles at each joint, as part of one plan for the arm during a point-to-point reach.

INTRODUCTION

The purpose of this study was to characterize motor patterns at the wrist during three-joint reaching movements in order to determine the general rules for coordination of the distal joint with its proximal joints. During planar reaching movements, the wrist joint appears to move very little (Cruse et al. 1993; Dean and Bruwer 1994). In order for motion at a joint to be minimal during a multijoint movement, muscle activities and torques at a joint must resist inertial effects arising from motion of adjacent joints. This has been demonstrated for movements in which subjects are instructed to actively keep one joint immobile in shoulder-elbow (Almeida et al. 1995; Gribble and Ostry 1999) and elbow-wrist movements (Latash et al. 1995). Evidence from one study (Koshland and Hasan 1994) suggests that this may also occur at the wrist during three-joint reaching movements when no instructions were given about joint motion. Reaches to targets in two directions were examined in this previous study and initial muscle activities were qualitatively appropriate to counteract inertial ef-

fects resulting from motion at proximal joints but torques were not computed. Although wrist muscle activities have been described for a range of directions of isometric 3-D forces (Delp et al. 1996) and 3-D wrist movements (Hoffman and Strick 1999), wrist muscle activities and torques have not yet been quantified across a range of planar directions of three-joint arm movements. This study tested the hypothesis that wrist muscle activities and torques would consistently resist proximal inertial effects such as to minimize wrist motion for all reaches. Given that muscle activities, torques, and excursions at the shoulder and elbow joints are known to vary across direction (Flanders 1991; Flanders et al. 1996; Gottlieb et al. 1997; Karst and Hasan 1991), it would be expected that wrist muscle activities and torques would also vary systematically across directions to resist the proximal inertial effects.

A second question addressed the pattern of wrist muscle activities. Wrist muscles have been shown to be coactive when resisting a changing load (Milner and Cloutier 1998; Milner et al. 1995) but shown to be reciprocal during reaches to two directions (Koshland and Hasan 1994). We tested the hypothesis that wrist muscles would be consistently activated in a reciprocal pattern for reaches across directions and in this manner they would be similar to proximal muscle patterns, suggesting similar rules at the three joints of the arm. To test the robustness of the wrist muscle pattern, inertial effects from proximal joints were blocked by immobilizing the wrist joint. We predicted that the reciprocal pattern would not be altered at first because the response to changes in inertial effects seems to require several trials, as shown with experiments with perturbed dynamic effects (Sainburg et al. 1999; Shadmehr and Mussa-Ivaldi 1994). After several trials of reaching with the wrist immobilized, however, we predicted that the wrist muscles would no longer be activated because a previous study showed that wrist muscles eventually became quiescent when the wrist was splinted for volitional elbow movements and perturbations of the forearm (Koshland et al. 1991). Results confirmed that wrist muscle torques consistently dampened proximal inertial effects across directions. Muscle activities were reciprocal and were not altered with wrist immobilization, even after many trials. The findings suggest that the nervous systems selects wrist muscles as part of a plan for the arm. Some of the results have been reported in abstract form (Koshland et al. 1995)

METHODS

Subjects, apparatus, and protocols

Four subjects (2 males and 2 females, 64–77 kg) performed point-to-point arm movements to targets in the horizontal plane (Fig. 1A).

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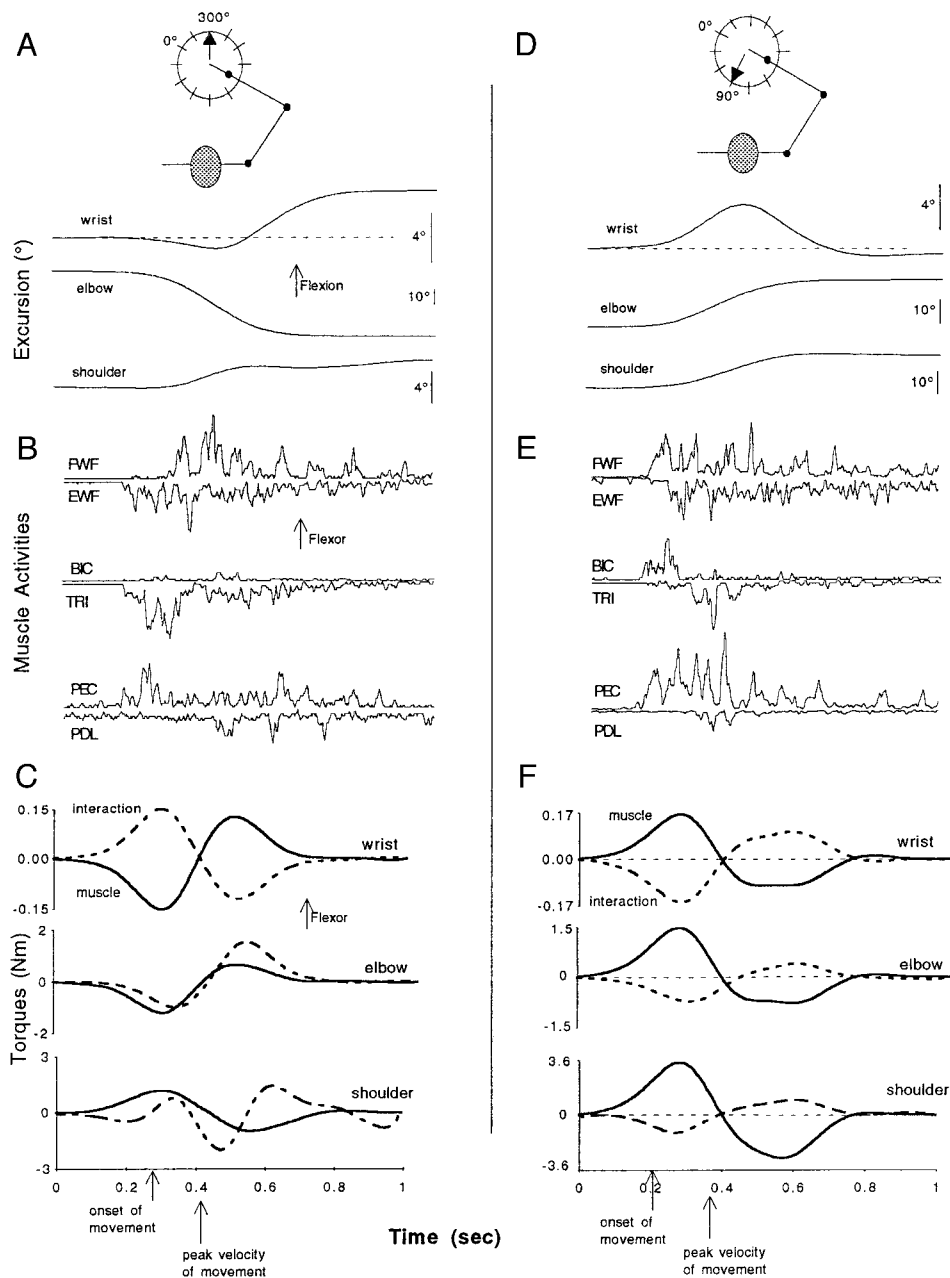


FIG. 1. Data for 2 representative trials from the same subject are shown. *A* and *D*: schematic figure of subject demonstrates direction of movement. Excursions, from distal to most proximal joint, are shown below, followed by muscle activities in *B* and *E* and torques at each joint in *C* and *F*. Upward deflections indicate flexion or flexor muscle activities and torques whereas downward deflections indicate extension or extensor muscle activities and torques. Vertical calibration bars for excursions indicate scaling of degrees. Muscle activities are scaled the same in *B* and *E*, except shoulder muscles in *E* are 10 times larger than in *B*. Muscle abbreviations are: pectoralis major (PEC), posterior deltoid (PDL), biceps brachii (BIC), triceps (TRI), flexors of wrist and fingers (FWF), and extensors of wrist and fingers (EWF). Time of onset of movement (10% of peak velocity) and of peak fingertip velocity are indicated by arrows on time axis.

Subjects gave informed consent and procedures were approved by the Human Subject Committee and were in accordance with the ethical standards enclosed in the Declaration of Helsinki. The apparatus and procedures have been described in detail (Koshland et al. 1999). Subjects sat in front of a table with the dominant right arm supported by a mechanical apparatus which rolled on the table. The apparatus allowed only horizontal flexion and extension at the shoulder, elbow, and wrist joints but no finger movement. An orthoplast splint held the forearm in supination and the hand in a vertical position with the fingers maintained in a slightly flexed posture and the index finger visible. The same initial configuration of the arm was used by a subject to reach to each of 12 equidistant targets (20 cm distance) at 30° intervals (Fig. 1). Subjects started with the wrist in neutral position and were instructed to make one quick movement without instructions regarding wrist motion or hand path. Six movements were performed to each target, totaling 72 movements for each subject. In another experiment performed on a different day, the double hinge joint in the apparatus underlying the wrist joint was locked, restricting

movement to the shoulder and elbow joints, and the same protocol was repeated (72 trials).

Kinematics and kinetics

Reflective markers were placed at locations along the right arm of the subject (index finger, wrist, elbow, and shoulder) and on the left shoulder. Movements were videotaped (120 Hz, 2 subjects; 60 Hz, 2 subjects) and digitized (Peak Performance Technologies). Angular displacements of the shoulder, elbow, and wrist joints were filtered using a fourth order critically damped filter at a 5-Hz cutoff. Equations of motion, adapted from Sainburg (Ghez and Sainburg 1995; Sainburg et al. 1995) to include the wrist joint, were used to calculate the generalized muscle and interaction torques at each of the three joints (see APPENDIX). The calculated muscle and interaction torques were plotted for each trial. The magnitude of the first peak in muscle torque was determined, along with the magnitude of interaction torque at the same time. These initial values were averaged for each direction and

subject. Because shoulder and elbow muscle torques have been described in previous studies (Buneo et al. 1995; Gottlieb et al. 1997), the comparison of wrist to elbow torques was emphasized in this study to highlight similarities/differences between distal and proximal joint torques.

Electromyographic activity

Bipolar surface electrodes were used to record electromyographic (EMG) activity of six muscles, generally a flexor and extensor at each joint. These included the following: pectoralis major (clavicular portion), posterior deltoid, biceps brachii, the lateral head of the triceps, the flexors of the wrist and fingers (FWF), and extensors of the wrist and fingers (EWF). The electrodes for the FWF (1 cm diam, 2 cm interelectrode distance) were placed on the forearm overlying the flexor carpi radialis and flexor digitorum superficialis muscles (see Koshland and Hasan 1994). The electrodes for the EWF were placed on the forearm overlying the extensor digitorum muscle. EMG signals were initially processed by preamplifiers ($1000 \times$ gain, band-pass of 10–2,500 Hz) and later rectified and smoothed (RMS, 4-ms window, Datapac-Run Technologies). Onsets of muscle activities were determined as the time when the EMG activity of a muscle exceeded a value $5 \times$ SD of its EMG during the first 100 ms after the go signal when the arm was at rest. Computer-derived onsets were verified by visual inspection. In addition, integrated area for the first 50 ms after the onset (Q50) was calculated (Gottlieb et al. 1996). The integrated area (Q50) was normalized to the largest value obtained during an experiment. A repeated measures analysis of variance (ANOVA; $P = 0.05$) was used to compare subject averages between wrist conditions (wrist free, wrist immobilized).

RESULTS

Individual movements

During an individual movement in which the wrist was free to move, the wrist joint typically showed little overall excursion, often 1–5°. Although the excursion was minimal, the wrist joint frequently experienced 1–2 joint reversals during the movement. This is most obvious for the movement to 90° in Fig. 1D for which overall wrist excursion was only 1° despite the fact that the wrist initially flexed 3° and extended 4°. In contrast, the excursions at the shoulder and elbow joints were typically monotonic. Even when excursions were minimal at a proximal joint such as the shoulder in Fig. 1A (4°), reversals did not occur.

The general pattern of EMG activities at the wrist joint was similar to the pattern at the shoulder and elbow joints (Fig. 1, B and E). Wrist muscles became active at the same time as proximal muscle activities, which occurred before the start of any joint motion. In addition, an initial reciprocal pattern was apparent at each joint. For example, wrist extensors were initially activated followed by wrist flexors in the movement to 300° (Fig. 1B), whereas the opposite sequence occurred for the movement to 90° (Fig. 1D). Later in the movement, both wrist muscle groups tended to remain active, resulting in coactivation.

The relationship of muscle to interaction torque differed among the joints. At the wrist the muscle torque mirrored the interaction torque throughout a movement (Fig. 1, C and F). Wrist muscle torque was at each moment nearly equal in magnitude but in the opposite direction (opposite sign) to that of the interaction torque at the wrist. In contrast, the torques at the shoulder and elbow showed various relationships but never

a perfect mirror image. For example in Fig. 1C, muscle and interaction torques at the elbow and shoulder joints were in the same direction for most of the movement. Even when muscle and interaction torques were in opposite directions, as in Fig. 1F, magnitudes were not equal and elbow and shoulder muscle torques were two and three times interaction torque, respectively.

Across directions

KINEMATICS/KINETICS. The pattern at the wrist was consistent for movements across directions. The wrist joint moved little during reaching movements to any of the 12 directions, except for 2 directions (120° and 270°) for which excursions reached 8–16° during individual trials for 2/4 subjects (Fig. 2A). Peak initial muscle torques at the wrist gradually changed across direction in a cosine-like tuning (Fig. 2B). Initial interaction torques across directions were equal in magnitude but of opposite sign to those of the muscle torque. Although instructed to make one quick movement, subjects typically varied speed from trial to trial. Nonetheless, subjects showed a similar variation across directions that was approximately ± 0.25 m/s for each subject. The slowest subject had an average speed of 1.0 m/s and lower magnitudes of interaction torques (triangular symbols in Fig. 2B). The quickest subject had an average speed of 1.5 m/s and the largest magnitudes of interaction torques (circular symbols in Fig. 2B). Regardless of the differences in speed, correlations of wrist muscle torque to wrist interaction torque resulted in Pearson r values of -0.99 to -1.0 for individual subjects (Fig. 2C).

Magnitudes of the wrist muscle and interaction torque were relatively small in this study, ranging from 0.05–0.3 Nm, one-tenth of the magnitude of elbow torques. Larger torques have been reported for vertical elbow-wrist movements with large wrist excursions, in the range of 0.5–1.0 Nm (Cooke and Virji-Babul 1995; Virji-Babul and Cooke 1995). To determine if the wrist interaction torques of this study were indeed significant in causing motion at the wrist, we estimated the kinematic effect from unopposed interaction torques at the wrist. Using the equation $A \times T^2/2I$ (where A = average interaction torque up to the first zero crossing, T = time to the first zero crossing, and I = moment of inertia of the hand at the wrist), wrist motion increased to an average of $27 \pm 13^\circ$ (SD). For directions with large interaction torques (e.g., 90 and 270°), excursion increased up to 40–50° and even for directions with small interaction torques (e.g., 180 and 330°), excursions increased by 2–22°. These excursions reflect estimates for the first phase of the biphasic interaction torque profile, unopposed by muscle torque. Given that the torque profile is typically symmetrical, the wrist would move an equal amount in the opposite direction during the second phase of the biphasic torque. In general, the estimates suggest that even though wrist torques were low in magnitude, interaction torques were sufficient to cause substantial movement at the wrist, and wrist muscle torques were sufficient to minimize the wrist motion.

The relationship of kinematics and kinetics across directions at the elbow joint were quite different from the wrist joint. Similar to previous reports (Buneo et al. 1995; Gottlieb et al. 1997), elbow joint excursions varied in a smooth progression across direction (Fig. 2D) and peak elbow muscle torques gradually changed across direction (Fig. 2E). The interaction

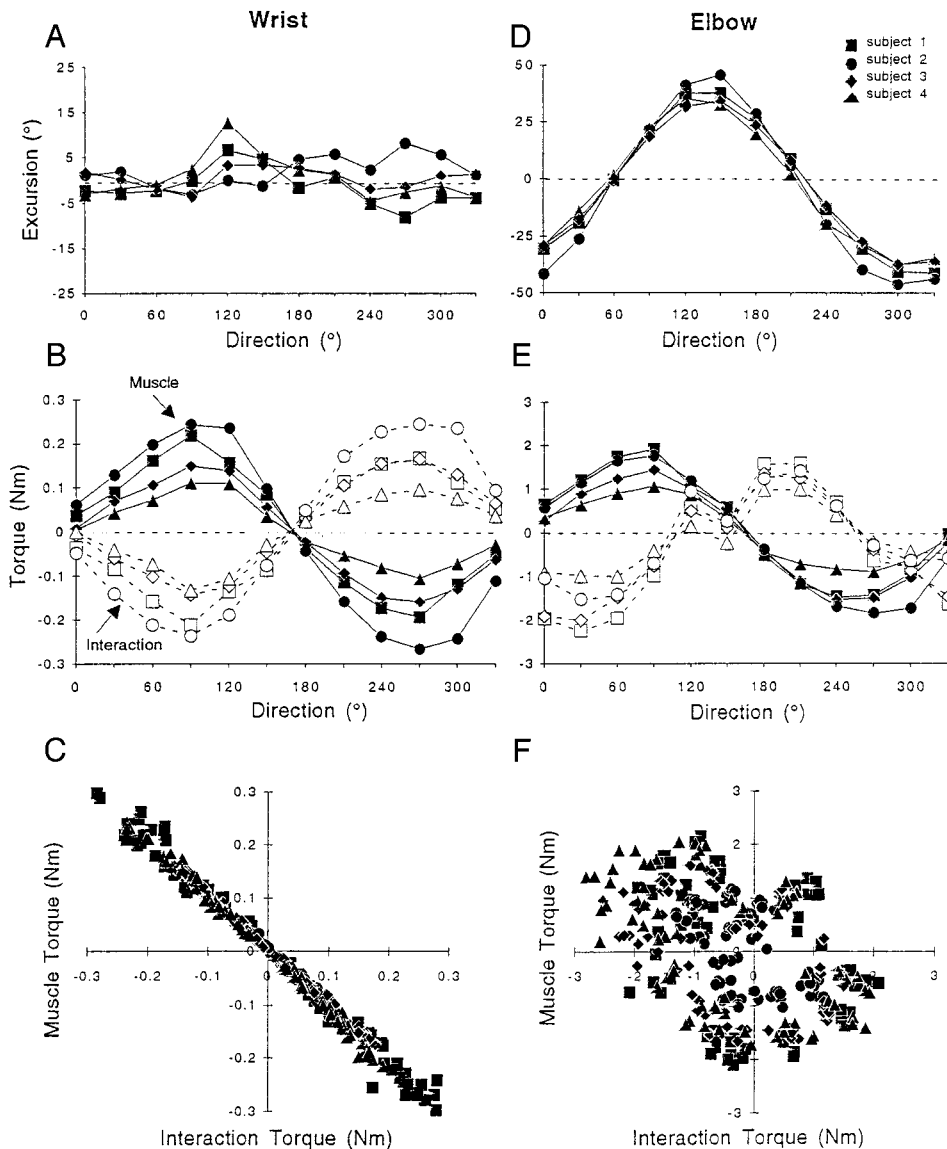


FIG. 2. Contrasting kinematics and kinetics at wrist vs. elbow joints across target directions. *A* and *D*: averaged joint excursions ($n = 6$) for each subject. *B* and *E*: similarly averaged values for first peak in muscle torque and interaction torque (at the same time as peak muscle torque). *C* and *F*: scatterplots in which the data points of muscle and interaction torque for each trial are plotted against each other.

torques, however, were not equal and opposite to muscle torques across directions. Interaction torque for a number of directions had the same sign as the elbow muscle torque (120, 150, and 270–300°). The largest interaction torque did not occur at the same direction with the largest and opposite peak muscle torque. Correlations of elbow muscle torque with elbow interaction torque were weak and ranged from -0.34 to 0.54 among subjects (Fig. 2*F*). These findings suggest that for many directions, elbow muscle torques either augmented or partially resisted interaction torques.

MUSCLE ACTIVITIES. To counteract interaction effects at the wrist, one strategy may have been to cocontract wrist muscles to stiffen the joint. As shown for individual trials in Fig. 1, *B* and *E*, reciprocal activation of wrist muscles typically occurred at the initiation of movement, with little cocontraction. Onsets of wrist and elbow muscles across directions are compared in Fig. 3, *A–D*. Wrist and elbow flexors muscles were activated first for movements to targets located medial to the arm (~ 0 – 180°), whereas wrist and elbow extensors initiated movements to targets that were lateral to the arm (~ 210 – 330°). Onsets of muscles at the three joints often followed a proximal to distal

sequence from shoulder to wrist (40% of trials). However, in 42% of all trials the wrist and elbow muscles switched order of onsets. Differences in onsets between flexor/extensor muscles at each joint were computed as a measure of initial cocontraction (Fig. 3, *E* and *F*). The time between flexor-extensor onsets gradually shifted across direction in a similar manner for both the wrist and elbow joints. Although differences in onsets at the wrist did not reach as large values as at the elbow, the differences were substantial between 30–119 ms, except two directions (30 and 90°) for which the differences were small (20 ms). If initial coactivity were a strategy to deal with interaction effects, one would predict that the difference in onset would covary with the magnitude of interaction torque in which the least difference in onset (greatest cocontraction) should occur at the direction with the largest interaction torque. However, the correlation between differences in onset and interaction torques was weak at the wrist (-0.52), similar to a weak correlation at the elbow (-0.37).

The most surprising results occurred in the other experiment in which the same subjects performed the reaching movements again but this time with the wrist joint mechanically locked in

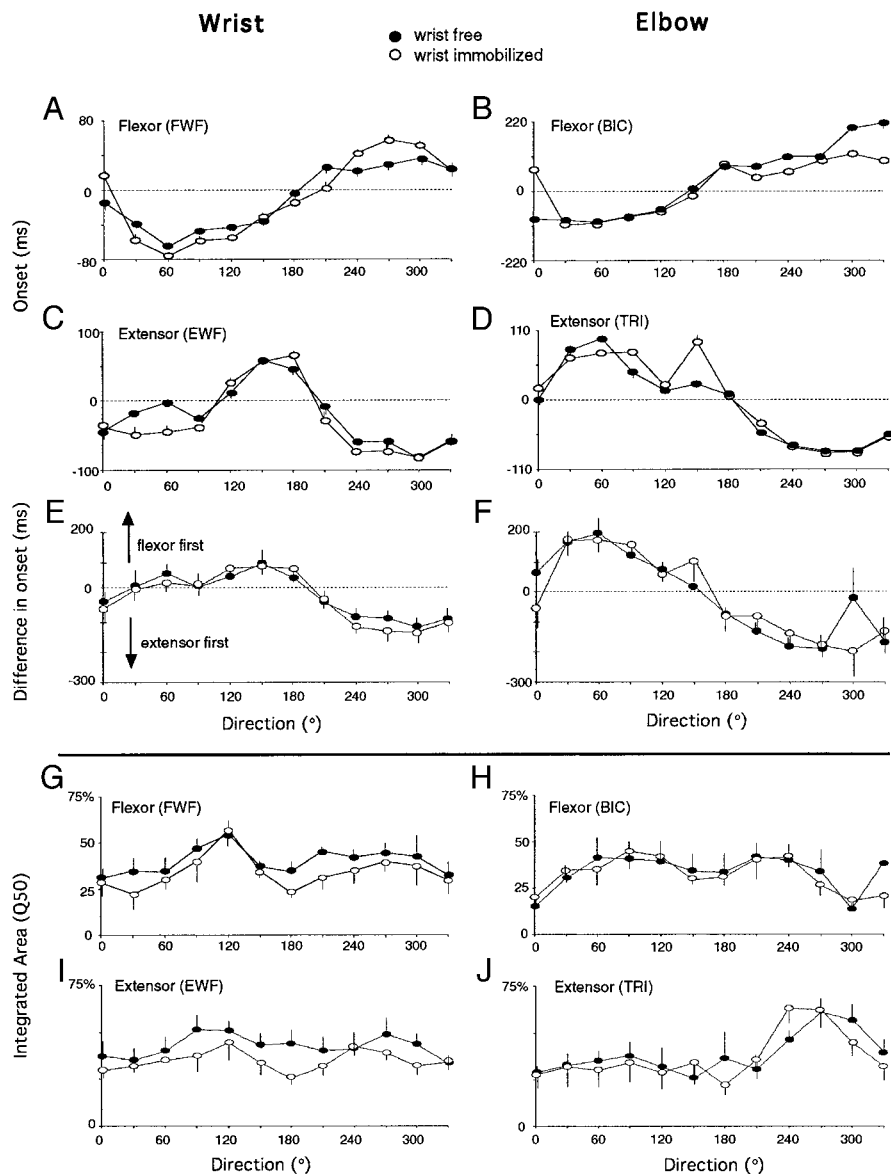


FIG. 3. Similarities of electromyographic (EMG) data for movements with wrist-free-to-move vs. wrist immobilized are shown. Each data point in this figure represents values averaged for the 4 subjects (6 trials/subject). ●: averaged values when wrist was free to move. ○: averaged values when wrist joint was immobilized in a neutral position. Vertical lines indicate SE. A–D: onsets of wrist and elbow muscles referenced to onset of movement (10% of peak fingertip velocity), indicated by 0 on y axis. Initial cocontraction, measured as difference in onset between flexor and extensor bursts, is shown for wrist (E) and elbow (F). Integrated areas over 1st 50 ms of each EMG burst, normalized to largest value recorded, are shown for wrist (G and I) and elbow (H and J) muscles.

a neutral position. Speeds of these two-joint movements with the wrist immobilized were similar to speeds with the wrist free and peak velocity averaged at 1.6 ± 0.8 m/s. It was remarkable that wrist muscle activities persisted in these experiments with the wrist immobilized for all 72 trials from each subject. Indeed, muscle activities in general were not altered, as shown in Fig. 3. Differences in onsets between flexors and extensors at the three joints did not change and no statistically significant differences were noted between the wrist free and wrist immobilized conditions (Fig. 3, A–F, shoulder not illustrated). Comparison of the integrated areas (Q50) demonstrated that initial amplitudes of EMG were also not altered with wrist immobilization, and no significant differences were found for any of the muscles (Fig. 3, G–J, shoulder not illustrated).

DISCUSSION

This study demonstrated that wrist motion was consistently restricted because wrist muscle torques matched interaction torques for movements to all directions. An alternative could

have occurred in which the wrist moved substantially for some or many directions and therefore muscle torque would not always match proximal interaction effects. It is possible for the wrist to move during reaching (Dean and Bruwer 1994; Koshland et al. 1994), so the fact that the wrist consistently did not move in this study reflects a choice by the nervous system, similar to the choice of a relatively straight hand path toward a target (Morasso 1981; Wadman et al. 1980; Wolpert et al. 1995). The choice to minimize wrist motion infers that the nervous system must select wrist muscles to resist proximal inertial effects, and unlike proximal muscles, the wrist muscles must completely dampen inertial effects. This coordination may be important for functional use of the hand because the inertial effects of the proximal segments would be less apt to disturb finger movement (Werremeyer and Cole 1997). Wrist muscle activities and torques, however, remain to be examined in a task in which grasping is combined with reaching.

A similar pattern of wrist muscle torques that counteracted interaction torques has been demonstrated for other multijoint

arm tasks in the vertical plane. These included instructed elbow-wrist movements (Virji-Babul and Cooke 1995) and cyclical elbow-wrist movements, both bidirectional and unidirectional patterns (Dounskaia et al. 1998). In these cases, the matching was not perfect and wrist motion occurred. Interestingly, when cats reached in the vertical plane to retrieve food from a well, wrist muscle torques counteracted interaction torques during the phases of the reach, but a perfect matching of muscle to interaction torque occurred during the last phase (Ghez et al. 1996). Moreover, the final wrist joint angle remained constant for reaches at different heights, whereas wrist muscle torques increased with increased interaction torques for the different heights much like results of this study in which muscle torques increased with increased interaction torques at different directions. No case of reaching has been described in which wrist muscle torques assisted interaction torques. The role of wrist muscles during a reaching task may then be to counteract proximal inertial effects. Depending on the requirements of the task for wrist motion or lack of motion, inertial effects are partially or completely dampened.

The wrist joint showed similar features to the proximal joints, suggesting that the wrist joint is included in a plan for the arm as a whole. Initial muscle activities at all joints began before limb displacement for movements to every direction, expanding earlier results for movements to two directions (Koshland and Hasan 1994). Moreover, muscles at each joint were consistently activated in an initial reciprocal pattern, similar to previous reports for shoulder-elbow (Flanders 1991; Flanders et al. 1996; Karst and Hasan 1991; Wadman 1980) or elbow-wrist movements (Latash et al. 1997; Virji-Babul and Cooke 1995). Wrist muscle torques varied in a cosine-like manner across direction, as previously reported for shoulder and elbow muscle torques (Buneo et al. 1995; Gottlieb et al. 1997). Moreover, onsets between flexor-extensor muscles and initial EMG amplitude at each joint gradually shifted across direction (Fig. 3), similar to other reports of changes in amplitudes and onsets of shoulder and elbow muscles across direction in the horizontal or vertical plane (Flanders 1991; Flanders et al. 1996; Karst and Hasan 1991; Wadman 1980). From the numerous similarities, the inertially coupled motions of flexion/extension at the three joints of the arm would seem to be generally controlled as a unit.

One explanation for the coupling among joints is that it results from biarticular muscles (Sergio and Ostry 1995; van Bolhuis et al. 1998). Most wrist muscles cross the elbow joint and may contribute to torque at the elbow. However, moment arms and the cross sectional area of wrist muscles are relatively small compared with elbow muscles and therefore they do not contribute a large portion to the resulting active elbow muscle torque (Amis et al. 1979; Ann et al. 1981; Loren et al. 1996). For a few wrist muscles the moment arm can even switch directions; for example, the moment arm of extensor digitorum changed from extensor to flexor at extended elbow angles. Nonetheless, it appears that the choice and amplitude modulation (AM) of wrist muscles closely followed the choice and modulation of elbow muscles across direction as shown in Fig. 3. In addition, wrist muscle torque profiles closely followed elbow muscle torque profiles (Koshland et al. 1999) despite differences of interaction torques (Fig. 2, *B* and *E*). In this manner, the similar modulation at the wrist and elbow joints suggests that control of the two joints are linked, probably

neurally and anatomically. A separate and parallel control of the wrist may arise when inertially uncoupled motions, such as pronation and supination, are important for orientation of the hand (Desmurget et al. 1996; Garvin et al. 1997; Lacquaniti and Soechting 1982; Sergio and Ostry 1995; Soechting and Flanders 1993).

In this study, the initial muscle activities were not altered when the wrist joint was immobilized. These findings could be explained by the fact that the initial configuration of the arm and the minimal wrist excursion did not change with wrist free or immobilized; however, it would also be expected that the muscles would become quiescent when they are no longer needed to keep the joint still. In contrast to previous reports of adaptations after several repeated trials (Sainburg et al. 1999; Shadmehr and Mussa-Ivaldi 1994), wrist muscle activities did not adapt after many repeated trials of this study. This suggests that the pattern of wrist muscles may reflect a plan of central origin which is in anticipation of inertial effects that would occur under normal circumstances. It is interesting that a pattern of initial reciprocal activation persisted at the wrist, suggesting that the nervous system's strategy to resist inertial effects was not to increase joint stiffness by initial cocontraction of muscles. The initial reciprocal activation characterized in this study seems typical because other studies report similar differences in agonist/antagonist onsets (60–100 ms) for proximal muscles during reaching movements (Wadman et al. 1980) and for wrist muscles during instructed elbow-wrist movements (Latash et al. 1995) and 3-D wrist movements (Hoffman and Strick 1999; Mustard and Lee 1987). The tendency for coactivity in wrist muscles observed later in the movement of this study has also been reported in elbow-wrist movements and 3-D movements (Hoffman and Strick 1999; Latash et al. 1995). Alternatively, subjects have used cocontraction to stiffen the wrist against an unstable load (Milner and Cloutier 1998; Milner et al. 1995), but they could not reach maximal stiffness and EMG levels when told to cocontract. Speculating from these single-joint cases, cocontraction may not be the optimal strategy to limit wrist joint motion during a multijoint reaching movement, and hence cocontraction of initial muscle activities was not observed in this study. Given the robustness of the muscle patterns at the three joints and their modulation across direction under unrestrained conditions, the neural system does not appear to reduce the three-joint arm to a simpler two-joint control system, despite its kinematic appearance.

APPENDIX

Shoulder:

$$\begin{aligned} \text{Self Torque}_{\text{shoulder}} &= [-(I_a + \Omega_3) - (\beta_6 + \beta_9 + \beta_1 \cos(\phi_w + \phi_e) \\ &\quad + (\beta_4 + \beta_5) \cos \phi_e) - (I_f + \Omega_2 + \beta_6 + \beta_2 \cos \phi_w \\ &\quad + (\beta_4 + \beta_5) \cos \phi_e) - (I_h + \Omega_1 + \beta_2 \cos \phi_w + \beta_1 \cos(\phi_w + \phi_e))] \cdot \ddot{\phi}_s \\ \text{Interacton Torque}_{\text{shoulder}} &= -(\beta_1 \sin(\phi_w + \phi_e) + (\beta_4 + \beta_5) \sin \phi_e) \\ &\quad \times \dot{\phi}_s^2 - (I_f + \Omega_2 + \beta_6 + \beta_2 \cos \phi_w + (\beta_4 + \beta_5) \cos \phi_e) \\ &\quad \times \ddot{\phi}_e - (\beta_2 \sin \phi_w - (\beta_4 + \beta_5) \sin \phi_e) \times (\dot{\phi}_s + \dot{\phi}_e)^2 - (I_h + \Omega_1 \\ &\quad + \beta_2 \cos \phi_w + \beta_1 \cos(\phi_w + \phi_e)) \cdot (\ddot{\phi}_e + \ddot{\phi}_w) + (\beta_2 \sin \phi_w \end{aligned}$$

$$\begin{aligned}
& + \beta_1 \sin(\phi_w + \phi_e) \cdot (\dot{\phi}_s + \dot{\phi}_e + \dot{\phi}_w)^2 + (\beta_{10} \sin \phi_s \\
& + \beta_7 \sin(\phi_s + \phi_e) \cdot \beta_3 \sin(\phi_s + \phi_e + \phi_w)) \cdot \ddot{x} - (\beta_{10} \cos \phi_s \\
& + \beta_7 \cos(\phi_s + \phi_e) \cdot \beta_3 \cos(\phi_s + \phi_e + \phi_w)) \cdot \ddot{y}
\end{aligned}$$

$$\text{Muscle Torque}_{\text{shoulder}} = -\text{Self Torque}_{\text{shoulder}} - \text{Interaction Torque}_{\text{shoulder}}$$

Elbow:

$$\text{Self Torque}_{\text{elbow}} = [-(I_f + \Omega_2) - (\beta_6 + \beta_2) \cos \phi_w] - (I_h + \Omega_1 + \beta_2 \cos \phi_w) \cdot \ddot{\phi}_e$$

$$\begin{aligned}
\text{Interaction Torque}_{\text{elbow}} = & -[\beta_1 \cos(\phi_w + \phi_e) + (\beta_4 + \beta_5) \cos \phi_e \\
& + \beta_6 + \beta_2 \cos \phi_w + I_h + \Omega_2 + \beta_2 \cos \phi_w] \cdot \ddot{\phi}_s - [\beta_1 \sin(\phi_w + \phi_e) \\
& + (\beta_4 + \beta_5) \sin \phi_e] \cdot \dot{\phi}_s^2 - (\beta_2 \sin \phi_w) \cdot (\dot{\phi}_s + \dot{\phi}_e)^2 - (I_h + \Omega_1 \\
& + \beta_2 \cos \phi_w) \cdot \ddot{\phi}_w + (\beta_2 \sin \phi_w) \cdot (\dot{\phi}_s + \dot{\phi}_e + \dot{\phi}_w)^2 + [\beta_7 \sin(\phi_s + \phi_e) \\
& + \beta_3 \sin(\phi_s + \phi_e + \phi_w)] \cdot \ddot{x} - [\beta_7 \cos(\phi_s + \phi_e) \\
& + \beta_3 \cos(\phi_s + \phi_e + \phi_w)] \cdot \ddot{y}
\end{aligned}$$

$$\text{Muscle Torque}_{\text{elbow}} = -\text{Self Torque}_{\text{elbow}} - \text{Interaction Torque}_{\text{elbow}}$$

Wrist:

$$\text{Self Torque}_{\text{wrist}} = [-(I_h + \Omega_1)] \cdot \ddot{\phi}_w$$

$$\begin{aligned}
\text{Interaction Torque}_{\text{wrist}} = & [-(I_h + \Omega_1)] + \beta_1 \cos(\phi_w + \phi_e) \\
& + \beta_2 \cos \phi_w] \cdot \ddot{\phi}_s - \beta_1 \sin(\phi_w + \phi_e) \cdot \dot{\phi}_s^2 - [(I_h + \Omega_1) \\
& + \beta_2 \cos \phi_w] \cdot \ddot{\phi}_s - \beta_2 \sin \phi_w \cdot (\dot{\phi}_s + \dot{\phi}_e)^2 + \beta_3 \sin(\phi_s + \phi_e \\
& + \phi_w) \cdot \ddot{x} - \beta_3 \cos(\phi_s + \phi_e + \phi_w) \cdot \ddot{y}
\end{aligned}$$

$$\text{Muscle Torque}_{\text{wrist}} = -\text{Self Torque}_{\text{wrist}} - \text{Interaction Torque}_{\text{wrist}}$$

SYMBOLS:

I = inertia; r = distance to center of mass from proximal joint

I = length; m = mass

$$\Omega_1 = m_h \cdot r_h^2$$

$$\Omega_2 = m_f \cdot r_f^2$$

$$\Omega_3 = m_a \cdot r_a^2$$

$$\beta_1 = m_h \cdot r_h \cdot l_a$$

$$\beta_2 = m_h \cdot r_h \cdot l_f$$

$$\beta_3 = m_h \cdot r_h$$

$$\beta_4 = m_h \cdot I_h \cdot l_a$$

$$\beta_5 = m_h \cdot r_f \cdot l_a$$

$$\beta_6 = m_h \cdot l_f^2$$

$$\beta_7 = m_h \cdot l_f + m_f \cdot r_f$$

$$\beta_8 = m_f \cdot l_a^2$$

$$\beta_9 = m_h \cdot l_a^2$$

$$\beta_{10} = m_a \cdot r_a + m_f \cdot I_a + m_h \cdot I_a$$

SUBSCRIPTS:

a = upper arm

f = forearm

h = hand

s = shoulder

e = elbow

w = wrist

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