

Research note

Coordination of mono- and bi-articular muscles in multi-degree of freedom elbow movements

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Abstract. We investigated the coordination of mono- and bi-articular muscles during movements involving one or more degrees of freedom at the elbow. Subjects performed elbow flexion (or extension) alone, forearm pronation (or supination) alone, and combinations of the two. In bi-articular muscles such as biceps brachii and pronator teres, the amplitude of agonist electromyographic (EMG) activity was dependent on motion in the two degrees of freedom. Agonist burst amplitudes for combined movements were approximately the sum of the agonist burst amplitudes for movements in the individual degrees of freedom. Activity levels in individual degrees of freedom were, in turn, greater than activity levels observed when a muscle acted as agonist in one degree of freedom and antagonist in the other. Other muscles such as triceps, brachialis, and pronator quadratus acted primarily during motion in a single degree of freedom. The relative magnitude and the timing of activity *between* sets of muscles also changed with motion in a second degree of freedom. These patterns are comparable with those reported previously in isometric studies.

Key words: Coordination – EMG – Multi-joint – Arm – Human

Introduction

Many muscles contribute to motion in more than one degree of freedom. Because there is no one to one mapping between muscle actions and kinematic degrees of freedom, central control signals must be coordinated to produce movements such as elbow flexion alone, forearm supination alone, or muscle cocontraction without motion (Flanagan et al. 1990). The electromyographic (EMG) correlates of this coordination have been reported previously in studies of isometric torques. In the

present paper we describe for isotonic movements the patterns of EMG activity for elbow muscles involved in flexion/extension and pronation/supination movements, both alone and in combination. We focus on the pattern of activity of individual muscles when they act as agonist in two degrees of freedom, in one degree of freedom only, and as agonist in one degree of freedom and antagonist in the other. The goal is to understand the organization of commands to mono- and bi-articular muscles which enable motion in both individual and multiple degrees of freedom.

Previous studies have examined muscle activity in a number of tasks that involve motion in multiple degrees of freedom. Van Zuylen et al. (1988) and Buchanan et al. (1986) reported the pattern of muscle activation during isometric torques in elbow movements of two degrees of freedom. Karst and Hasan (1991) described activity patterns of two-joint muscles during motion at both joints. Karst and Hasan reported that changes in the relationship between the EMG magnitudes of biceps brachii and brachioradialis depended on both elbow and shoulder motion. Biceps activity was greatest when it participated as agonist at the two joints and was less when it served as agonist at one joint and antagonist at the other. The overall magnitude of EMG activity thus appears to reflect a net contribution to motion in relevant degrees of freedom.

Van Zuylen et al. (1988) reported motor unit recruitment thresholds during isometric contractions in two-degree-of-freedom elbow movements. They identified subpopulations of motor units in elbow muscles whose recruitment thresholds in one degree of freedom varied with the torque exerted in a second. For example, recruitment thresholds for biceps long head motor units varied depending on torques in both flexion and supination directions. Other subpopulations of motor units had thresholds that were dependent on torques in one degree of freedom only. The activation of different subpopulations of motor units may provide a neuroanatomical mechanism subserving multiple-degree-of-freedom movements about a single joint.

Materials and methods

Procedure

Subjects made forearm movements in a sagittal plane that involved flexion (or extension) alone, pronation (or supination) alone and combinations of the two. EMG patterns associated with these movements were recorded from eight mono- and bi-articular elbow muscles. Arm position was recorded in three dimensions using an Optotrak system (Northern Digital).

In movements involving flexion or extension alone the forearm was either fully pronated, semi-pronated, or fully supinated. The flexions started from a position 45° below the horizontal plane and ended at targets located 45° above the horizontal plane. Start and end positions were reversed for extension movements. The movements were performed with the upper arm vertical and then repeated with the upper arm in a horizontal plane. When the upper arm was horizontal the initial forearm position was either 45° out from a vertical plane or 45° behind it. In order to insure that movements were limited to the two degrees of freedom about the elbow, a brace was used to restrict wrist motion and subjects were instructed to hold the upper arm still to reduce shoulder motion. Target positions for flexions and extensions were specified using plastic washers hung from the ceiling.

In movements involving pronation or supination alone, the forearm was held either in an extended position 45° below the horizontal plane or in a flexed position 45° above the horizontal plane. The movements consisted of full and half (to the semiprone position) pronations and full and half supinations. The movements were performed with the upper arm vertical and repeated with the upper arm horizontal.

In movements combining flexion/extension with pronation/supination, subjects started from 45° below the horizontal plane (flexion movements) with the forearm either fully pronated or fully supinated. Subjects flexed the arm while simultaneously supinating or pronating and ended at a target located 45° above the horizontal plane. Both full and half pronations and supinations were collected with start and end being reversed for extensions. Vertical and horizontal upper arm positions were used. In total, 220 trials were collected for each subject. Subjects were instructed to move quickly and were allowed rest periods between conditions. Five subjects were tested.

Muscle activity recording

EMG activity patterns were recorded from muscles about the elbow using bipolar surface electrodes (Neuromuscular Research Center). Recordings were made from the following eight muscles in subjects 1–3: triceps brachii (lateral head), biceps brachii (long head), biceps brachii (short head), brachialis, brachioradialis (except in subject 1), anconeus, pronator teres, and pronator quadratus. In subjects 4 and 5 recordings were made from the muscles listed above, but brachioradialis was replaced by the medial head of the triceps. Electrode placement was verified by having subjects perform test manoeuvres (Delagi 1980). EMG signals were sampled at 1200 Hz, digitally band-pass filtered between 20 and 300 Hz, rectified, and integrated off-line.

Movement recording and analysis

The position of the upper body and the arm were recorded in three dimensions using Optotrak. Infrared-emitting diodes (IREDs) were placed on the subject's torso and upper arm; five to six IREDs were used to define each structure. The motion of the forearm was obtained using a lightweight transparent plastic (Plexiglas) apparatus strapped to the wrist. IRED positions were sampled at 100 Hz.

Orientation angles of the upper and lower arms were calculated from raw data using a vendor supplied rigid body algorithm based on the method of quaternions (Horn 1987). Lower arm motion was specified relative to the upper arm: an angle of 0° pitch corresponded to a right angle at the elbow; an angle of 0° roll corresponded to the forearm in a semi-prone position. Upper arm motion was specified relative to the torso: an angle of 0° corresponded to the upper arm aligned with the frontal plane.

Kinematic analyses were carried out on the orientation angles of the lower arm. The orientation angle of the upper arm was used to verify that movements were initiated from either 0° or 90°, as instructed, and changed little during the trial. The orientation angles were numerically differentiated by the use of the least squares method (Dahlquist and Björck 1969, their Eq. 7.2.8). Kinematic records were scored for movement onset and offset using 10% of maximum velocity.

EMG analysis

EMG signals were scored for the onset and offset of the first burst of activity displayed by a muscle. Burst onset was scored as the point on the EMG record 2 standard deviations above the baseline level prior to movement. Burst offset was the point at which the EMG signal returned to baseline. Amplitude of EMG activity is the area under the curve between these two points. In 10–20% of trials in which flexion/extension was combined with pronation/supination, muscles that acted as agonist in the two degrees of freedom (e.g. biceps in combined flexion/supination) displayed an EMG activity pattern that did not return to baseline until the end of the movement. In other similar trials, where EMG did return to baseline, the offset of the first agonist burst corresponded closely to both the onset of antagonist activity and the peak velocity of movement. Thus, for purposes of data analysis, the burst offset was scored at the point of peak velocity in trials that displayed an extended agonist burst.

Results

The patterns of muscle activity in movements involving flexion (or extension) alone, pronation (or supination) alone, and combinations of the two are shown in Fig. 1 for a representative subject. The upper panel gives the amplitudes of individual agonist bursts as a function of the magnitude of elbow movement. Each of the upper panel plots is divided into four quadrants in which EMG amplitude is shown for various movement combinations. For example, in Fig. 1C, biceps EMG amplitude for movements involving supination and extension is shown at the lower right; movements involving supination plus flexion are shown at the upper right. The EMG amplitudes for flexion alone, extension alone, pronation alone and supination alone are shown along the axes. The lower panel presents the mean EMG amplitude for all movement combinations for the same subject. Mean activity is shown for trials involving supination plus extension, supination alone, supination plus flexion, etc.

Muscle activity patterns fell into two categories. An example of the first activity pattern is shown for the medial head of triceps in Fig. 1A,B. It can be seen that the level of triceps activity was greatest and similar in magnitude for all movements involving extension, regardless of whether these occurred in isolation or were combined with forearm pronation or supination. Muscles such as

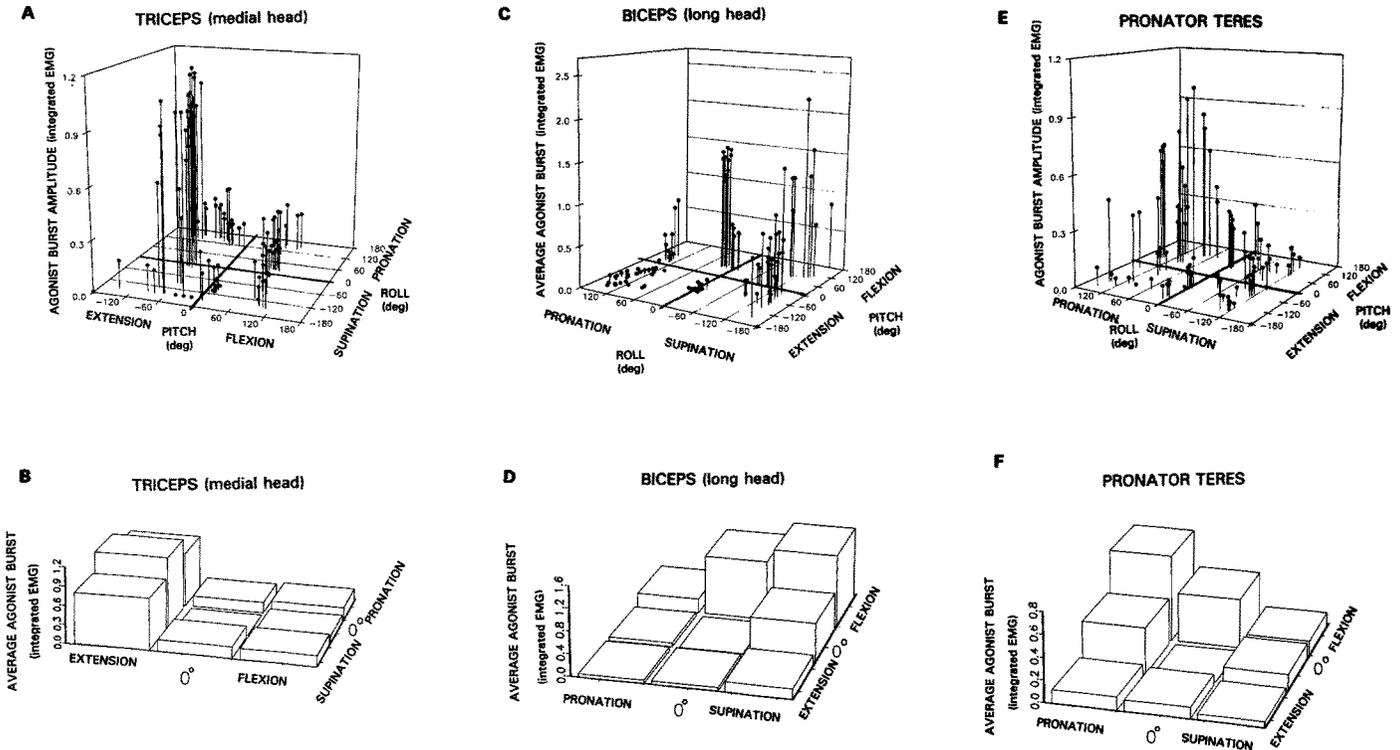


Fig. 1A-F. Agonist electromyographic (EMG) amplitudes for mono- and multifunctional elbow muscles. A, C, E EMG amplitudes for combinations of elbow flexion/extension, pronation/supination. B, D, F Mean EMG amplitudes for combined move-

ments, for flexion and extension alone (0° along the supination/pronation axis), and for supination and pronation alone (0° on the flexion/extension axis)

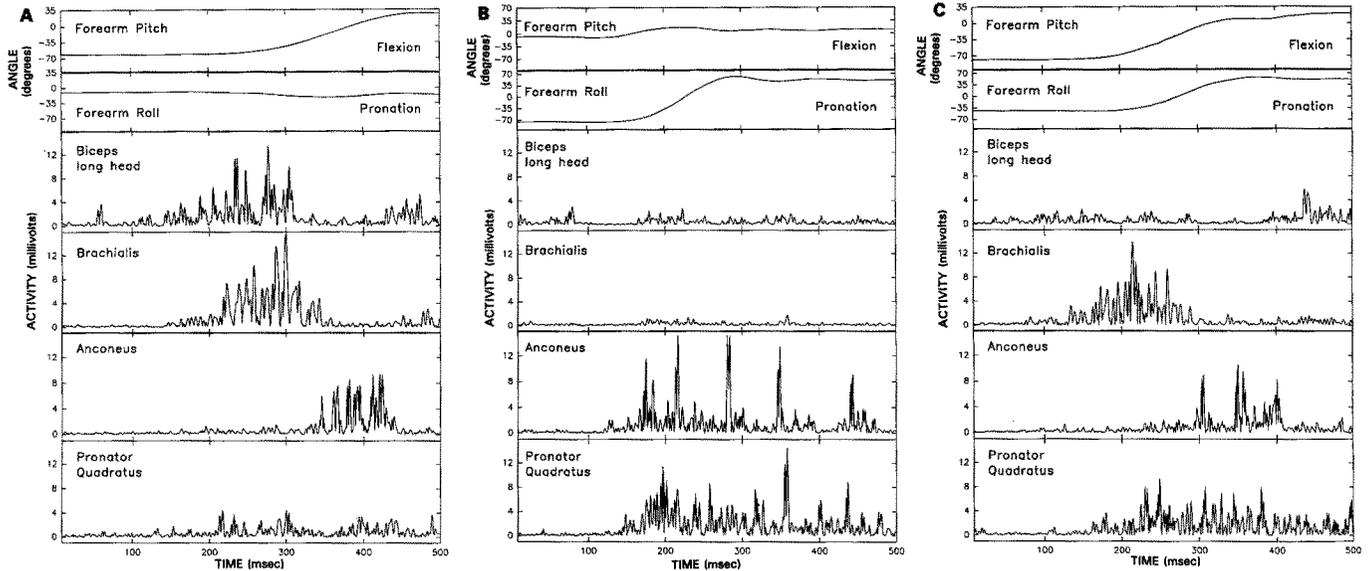


Fig. 2. Kinematic patterns and EMG activity for elbow flexion alone (A), forearm pronation alone (B), flexion and pronation (C). See text for details

the medial head of triceps were active as agonists for movements in one degree of freedom only. A simultaneous movement in another degree of freedom (e.g. pronation or supination) did not affect the amplitude of the burst. These muscles can be characterized as mono-functional, as their activity corresponds primarily to motion in a single degree of freedom. Muscles which dis-

played monofunctional patterns of activity included medial and lateral head of triceps (elbow extension), brachialis (elbow flexion) and pronator quadratus (forearm pronation). All subjects tested thus far have shown similar patterns for these muscles ($P > 0.01$, in all but one case). (Note that muscles that were classified here as mono-functional may act as bi-functional muscles in

movements involving degrees of freedom not examined in the present study.)

An example of the second kind of activity pattern is shown for the long head of biceps and pronator teres in Fig. 1C–F. EMG burst amplitude for pronator teres is greatest during a flexing pronation in which the muscle acts as agonist in both degrees of freedom. The activity level is less during pronation or flexion alone and still less for pronating extensions and supinating flexions, where pronator teres acts as agonist in one degree of freedom and antagonist in the other. Similarly, for biceps, which is a forearm supinator as well as an elbow flexor, activity is greatest during a supinating flexion. Activity is less during supination or flexion alone, and even less during supinating extensions and pronating flexions in which the muscle serves as agonist in one degree of freedom and antagonist in the other.

Multifunctional muscles such as biceps and pronator teres display a pattern of activity in which the amplitude of the agonist burst is affected by movements in more than one degree of freedom. This pattern was also seen in biceps short head. These same basic patterns have been observed for all subjects ($P < 0.01$). Note, in the present context the term multifunctional is used only to designate muscles that show *phasic* activity for motions in the two degrees of freedom.

The relative magnitude and timing of muscle activity differed in one- and two-degree-of-freedom elbow movements. Figure 2 shows, again for a single subject, activity patterns for four muscles involved in elbow flexion alone, pronation alone, and combined elbow flexion and pronation. During flexion (Fig. 2A) biceps and brachialis act as agonists, anconeus acts as an antagonist and pronator quadratus shows little activity. During pronation (Fig. 2B) anconeus and pronator quadratus are agonists while biceps and brachialis show little activity. Note, there is complete suppression of biceps activity prior to the onset of pronator quadratus. During combined pronation and flexion (Fig. 2C), the relationships differ from either flexion alone or pronation alone. Specifically, in three of the subjects tested to date the magnitude of brachialis activity during flexing pronations increased relative to its magnitude during flexion alone ($P < 0.01$). In addition, in two subjects, brachioradialis activity was significantly greater during flexing pronations than in flexion alone ($P < 0.01$). Thus, the relationship between biceps and brachialis or brachioradialis may change, depending on whether elbow flexion occurs alone or is accompanied by pronation. That is, the activity pattern of muscles that have a single mechanical action is nevertheless affected by movement in another degree of freedom. This may occur to compensate for the reduced agonist burst amplitude of the biceps, a supinator, during the pronation movement. This general pattern is also observed in other sets of muscles, where the multifunctional muscle acts as agonist in one degree of freedom and antagonist in the other.

During combined flexion and pronation, the patterns of anconeus and pronator quadratus activity also change relative to flexion or pronation alone. Anconeus acts as an antagonist during flexion alone, whereas pronator

quadratus shows little activity. Anconeus and pronator quadratus are agonists during pronation alone and antagonists during combined pronation and flexion. This pattern was also observed for pronator quadratus and pronator teres which acted as agonists during pronation and antagonists during flexing supinations. Thus, muscles that act as agonists in one movement may act as antagonists in another.

Discussion

Muscles such as triceps, brachioradialis and pronator quadratus acted primarily during motion in a single degree of freedom at the elbow, and their activity was modulated little by motion in the other degree of freedom. In other muscles, such as biceps and pronator teres, the amplitude of the agonist burst was dependent on motion in the two degrees of freedom. For these muscles, the amplitude was greatest when the muscle acted as agonist in both degrees of freedom, less when the muscle acted as an agonist in a one degree of freedom movement and still less when the muscle served as agonist in one degree of freedom and antagonist in the other.

Comparable findings have been obtained in the isometric case with respect to both recruitment thresholds (van Zuylen et al. 1988) and EMG activity (Buchanan et al. 1986). Van Zuylen et al. showed that elbow muscles, such as supinator, had motor units whose recruitment thresholds depended only on motion in one degree of freedom. Other muscles, such as pronator teres, had motor units whose recruitment thresholds depended on motion in two degrees of freedom. For example, when subjects maintained a pronation torque while producing a flexion torque, motor unit recruitment thresholds in pronator teres were less than when subjects maintained a supination torque while producing a flexion torque. Similarly, Buchanan et al. (1986) reported that EMG activity in muscles such as medial triceps was greatest during combined isometric elbow torques in the valgus (external rotation about the humerus) and extension directions, less in extension or valgus alone, and less still in valgus and flexion directions. Thus, recruitment thresholds were less and EMG activity was greater when muscles acted as agonists in two degrees of freedom than when they acted as an agonist in one degree of freedom and antagonist in the other.

In addition to the dependence of individual muscles' activity on motion in multiple degrees of freedom, the relative magnitude and the timing of activity *between* sets of muscles also changed with motion in a second degree of freedom. For example, when mono- and multifunctional muscles, such as the brachialis and biceps, acted synergistically, brachialis compensated for biceps in movements such as flexing pronations where biceps activity was reduced. A comparable finding was reported by Karst and Hasan (1991). The EMG magnitude of the double-joint biceps was reduced relative to the single-joint brachioradialis for a movement involving flexion at the elbow and extension at the shoulder.

The general similarity of the patterns reported in pre-

vious isometric studies and those observed in the present isotonic study, raises the question of whether the motor unit subpopulations identified by van Zuylen et al. (1988) can account for the EMG patterns observed during motion in multiple degrees of freedom. These subpopulations may well provide a neuroanatomical substrate for the patterns observed in the present study. However, regardless of the specific subpopulations which are activated, the mechanical action of bi-articular muscles results in motion in multiple degrees of freedom. Thus, in order to produce motion in individual degrees of freedom, the central control signals to muscles must be coordinated (see Flanagan et al. 1990, for a scheme for this coordination in the context of human jaw motion).

The electromyographic patterns obtained in the present study help to illustrate how commands might be organized for multiple-degree-of-freedom movements. Specifically, we have observed that for movements in which a muscle acts as agonist in two degrees of freedom, the EMG amplitudes are approximately the sum of the amplitudes seen for movements in the component degrees of freedom. The additivity observed in EMG amplitudes suggests that the central commands corresponding to motion in individual degrees of freedom may themselves be additive.

We have described patterns of kinematic and EMG activity for elbow motion in multiple degrees of freedom. These patterns which are readily measurable experimentally, offer an insight into control, but presumably neither are controlled variables: EMG varies with load and with the position of the limb; kinematic patterns reflect a combination of dynamics, muscle mechanical properties, reflexes and central commands. Both EMG and kinematics presumably arise from independently specified central control signals which may correspond to the regulation

of the motoneuron recruitment threshold lengths of muscles (Feldman 1986). The relationship between central commands and the resulting kinematics and EMG patterns in multi-joint arm movements is treated in Feldman et al. (1990) and Flanagan et al. (1990).

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