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RESEARCH NOTE

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Independent coactivation of shoulder and elbow muscles

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Abstract The aim of this study was to examine the possibility of independent muscle coactivation at the shoulder and elbow. Subjects performed rapid point-to-point movements in a horizontal plane from different initial limb configurations to a single target. EMG activity was measured from flexor and extensor muscles acting at the shoulder (pectoralis clavicular head and posterior deltoid) and elbow (biceps long head and triceps lateral head) and flexor and extensor muscles acting at both joints (biceps short head and triceps long head). Muscle coactivation was assessed by measuring tonic levels of electromyographic (EMG) activity after limb position stabilized following the end of the movements. It was observed that tonic EMG levels following movements to the same target varied as a function of the amplitude of shoulder and elbow motion. Moreover, for the movements tested here, the coactivation of shoulder and elbow muscles was found to be independent – tonic EMG activity of shoulder muscles increased in proportion to shoulder movement, but was unrelated to elbow motion, whereas elbow and double-joint muscle coactivation varied with the amplitude of elbow movement and were not correlated with shoulder motion. In addition, tonic EMG levels were higher for movements in which the shoulder and elbow rotated in the same direction than for those in which the joints rotated in opposite directions. In this respect, muscle coactivation may reflect a simple strategy to compensate for forces introduced by multijoint limb dynamics.

Key words Cocontraction · Electromyography · Joint stiffness · Human multijoint movement

Introduction

The ability to coactivate limb muscles provides the nervous system with a way to adapt the limb to changing environmental conditions. Coactivation changes mechanical impedance and, hence, may stabilize the limb in the face of external perturbing forces and forces arising from multijoint dynamics. Evidence to date based on studies of limb stiffness in statics suggests that the control of impedance is restricted to rather global adjustments of the impedance of the limb as a whole (Mussa-Ivaldi et al. 1985). The purpose of the present study was to re-examine this issue in the context of muscle coactivation and, in particular, to assess the possibility of independent coactivation at the shoulder and elbow.

Both behavioral and electrophysiological studies support the idea that muscle coactivation may be controlled independent of movement. Subjects are able to coactivate antagonist muscles to stabilize a single joint in the face of loads (for example, Latash 1992; Milner and Cloutier 1993). Neurons in both precentral cortex and cerebellar cortex have been found that discharge in relation to the coactivation of antagonistic muscles, but not to reciprocal activation (Humphrey and Reed 1983; Frysinger et al. 1984). Deluca and Mambrito (1987) report that motor units associated with antagonist muscles show a ”common drive”, suggesting that joint impedance may be controlled by the simultaneous activation of antagonist motoneuron pools.

In this context, it is somewhat surprising that subjects display a rather limited ability to voluntarily control limb impedance separately at different joints. While subjects can increase or decrease the overall level of limb impedance (represented as stiffness ellipses at the hand), they are unable to change the orientation of the stiffness ellipse and, hence, the balance of impedance at the shoulder and elbow joints (Mussa-Ivaldi et al. 1985, but cf. Gomi and Osu 1996). However, differences in the relative levels of shoulder- and elbow-joint impedance may not be well reflected in the shape of the hand stiffness ellipse, which is largely determined by limb geometry (Flash and Mussa-Ivaldi 1990). In the present study, we further examine the determinants of shoulder and elbow impedance by using electromyography to measure muscle coactivation.

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We assessed the coactivation of muscles spanning the shoulder and elbow joints by measuring tonic levels of electromyographic (EMG) activity following multi-joint movement. Our strategy was to have subjects make movements from different initial limb configurations to a single final target. Using a single final target controls for the possibility that differences in tonic EMG levels arise from different final limb positions.

We specifically address three questions. First, do tonic levels of EMG activity vary with the magnitude and direction of shoulder and elbow movement? Second, is there evidence that shoulder and elbow muscles may be coactivated independently? Third, we address whether muscle coactivation may be used to stabilize the limb to offset forces arising from multijoint dynamics. As a consequence of limb dynamics, interaction torques at the shoulder are high during ”swinging” movements, in which the shoulder and elbow rotate in the same direction, and low during ”reaching” movements, in which the joints move in opposite directions (Hollerbach and Flash 1982; Sainburg et al. 1995). We thus compare tonic EMG levels and corresponding interaction torques for reaching and swinging movements.

Materials and methods

The experimental procedures used in these studies have been approved by the ethics committee of the Department of Psychology, McGill University.

Movement task

Six subjects performed pointing movements to targets in a horizontal plane containing the shoulder. Subjects were instructed to raise their arm slightly above a tabletop, in which targets were embedded, and to move as rapidly as possible from one of 14 different initial limb configurations to a single target so that, at the end of each movement, the limb configuration was the same. At the target position, the shoulder angle was 45°, and the elbow angle was 70°. Shoulder angles were defined relative to the frontal plane, such that increasing values corresponded to greater amounts of shoulder flexion. Elbow-joint angles were defined relative to the upper arm. Zero degrees corresponded to full extension of the lower arm and positive values were associated with flexion.

The initial limb configurations were chosen so that the magnitude and direction of shoulder and elbow rotation were systematically varied. Subjects performed movements involving five levels of shoulder rotation (20° and 40° flexions, 20° and 40° extensions and no shoulder movement) combined with three levels of elbow rotation (0°, 20° or 40° of flexion).

Subjects were instructed to move as rapidly as possible from a specified initial configuration to the target without making corrections and to briefly hold their arm at the target position after the end of movement. Subjects were free to view their arm during the experiment. Twenty trials per condition were collected with numerous rest periods to reduce fatigue.

Data analysis

Motions of the torso, lower and upper arm were recorded at 200 Hz using an Optotrak system and were used to compute shoulder- and elbow-joint angles over time. Joint kinematics were digitally low-pass filtered at 12 Hz using a second-order butterworth filter implemented on a digital computer using Matlab.

Electromyographic activity of six arm muscles was measured using bipolar surface electrodes (Neuromuscular Research Center). Recordings were made from the posterior deltoid (single-joint shoulder extensor), clavicular head of pectoralis (single-joint shoulder flexor), biceps long head (double-joint flexor acting primarily at the elbow), triceps lateral head (single-joint elbow extensor), biceps short head (double-joint flexor) and triceps long head (double-joint extensor). Electrode placement was verified by test manoeuvres. Placements for one-joint muscles were verified by observing EMG activity for movements about that joint alone, while placements for double-joint muscles were verified by observing EMG activity for movements about either the shoulder or elbow joint. For biceps long head, electrodes were positioned such that activity was observed in relation to elbow movement and was minimal during motion at the shoulder. EMG signals were analog low-pass filtered at 600 Hz, sampled at 1200 Hz, digitally band-pass filtered between 30 and 300 Hz and full-wave rectified.

Individual movements were aligned at movement end, which was scored using the tangential velocity of the hand. Tonic EMG levels following movement were determined for each of the six muscles by computing the mean level of EMG activity during a 100-ms period after movement end, once the limb was stationary. The analyses were also repeated using larger data windows. The basic pattern of results was similar to that reported below.

For each trial, a single mean value was computed for each muscle representing tonic activity following movement. To enable comparison of EMG levels between muscles and across subjects, these values were normalized to z-scores. For each subject, mean tonic levels for each muscle were normalized based on the set of mean values for that muscle over the entire experiment. The effect of this normalization was to eliminate differences in the mean and standard deviation of tonic EMG levels among different muscles and across subjects.

To verify that the patterns of results reported below were not due to the normalization procedure, the analyses were repeated by normalizing tonic EMG levels in two other ways: to maximum cocontraction levels (recorded in a separate procedure) and to the maximum phasic EMG level observed for each muscle over the course of the experimental trials. In both cases, the results were the same as those reported below.

To quantify the level of coactivation about the shoulder, normalized tonic EMG levels of deltoid and pectoralis were averaged. Similarly, normalized tonic activity of biceps long head and triceps lateral head were averaged to characterize elbow coactivation. To assess the coactivation of double-joint muscles, normalized tonic EMG activity of biceps short head and triceps long head were averaged.

Prior to this calculation, as a control for the possibility that patterns of tonic activity may be influenced by the presence of reciprocal muscle activity, correlation coefficients were calculated on a per-trial basis between individual flexor and extensor muscle pairs during the 100-ms measurement period. In cases where a significant negative correlation was observed ($P<0.01$), the data from those muscle pairs were excluded from the analysis. This procedure resulted in the elimination of 12% of the data.

Biceps long head acts primarily at the elbow (Yamaguchi et al. 1997). However, since both heads of the biceps cross the glenohumeral joint, the long head may exert torque about the shoulder as well as the elbow (Wood et al. 1989a,b; Yamaguchi et al. 1990). In a control study, the experiment was repeated with EMG activity recorded from the brachioradialis, a true single-joint elbow flexor, as well as each of the muscles listed above. All other procedures were similar. Data from five subjects were collected, and patterns of muscle coactivation were examined using brachioradialis rather than biceps long head.

Results

The data were examined to assess the dependence of tonic EMG on movement amplitude, the independence of tonic EMG at the shoulder and elbow and the degree to

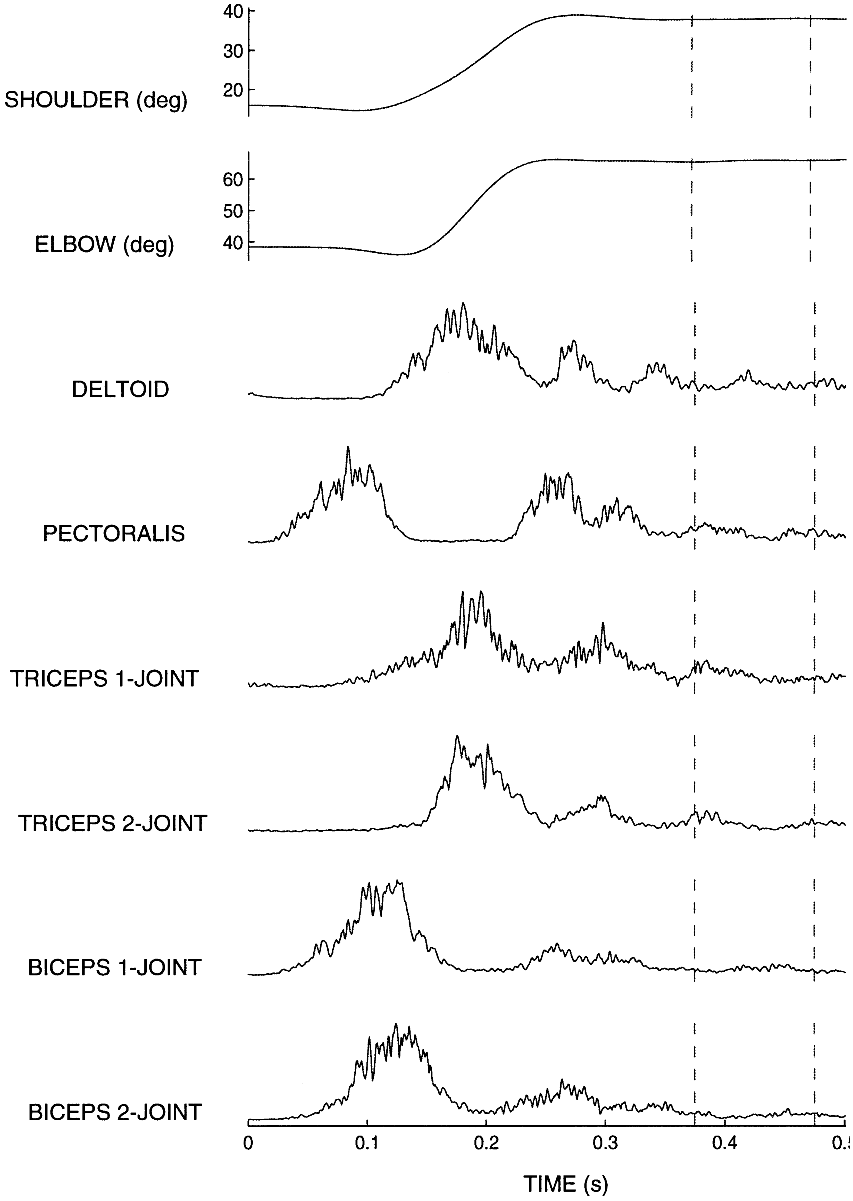

Fig. 1 Data for a single subject, showing mean joint angles and mean EMG activity as a function of time for a single-movement condition. *Vertical dotted lines* bracket the portion of data used to measure tonic EMG levels. Trials were excluded from analysis if a significant negative correlation between tonic levels in flexor and extensor muscle pairs was observed during the measurement window (see text)

which tonic EMG levels vary with interaction forces arising from limb dynamics.

Figure 1 shows a sample of mean shoulder and elbow angles as well as mean EMG activity as a function of time for a single condition in which the joints move in the same direction (flexion). An initial phasic EMG burst was seen in agonist muscles prior to movement onset and was followed by phasic activity of antagonist muscles which decelerate the limb. After the cessation of phasic EMG activity and once the final limb position was obtained, a relatively constant tonic EMG level was observed. It was during this period (indicated in Fig. 1 by vertical dashed lines) that mean tonic EMG activity was computed (the average range of variation in joint angle during this interval was ±0.56° for the shoulder and ±0.58° for the elbow). Note that the measurement of tonic EMG was conducted on the basis of individual records. Figure 1 shows average values for visualization purposes only.

Figure 2A shows mean tonic EMG activity as a function of initial limb configuration, averaged over all six subjects (consistent patterns were seen across subjects). Note that the data are separated into three groups for clarity of presentation only – all data points were included together in the analyses reported below. The level of tonic EMG activity following movements to the same target was seen to change depending on the initial configuration of the limb. Shoulder muscles showed a U-shaped function, which mirrors shoulder movement amplitude, while elbow and double-joint muscles showed a monotonic pattern, which mirrors elbow-movement amplitude (see panel B). Thus, the pattern of coactivation of shoulder muscles appears to be different than that of elbow and double-joint muscles (see also Gomi and Osu 1996).

To explore the relationship between tonic EMG levels and joint movement amplitude, mean movement amplitudes were computed for movements associated with

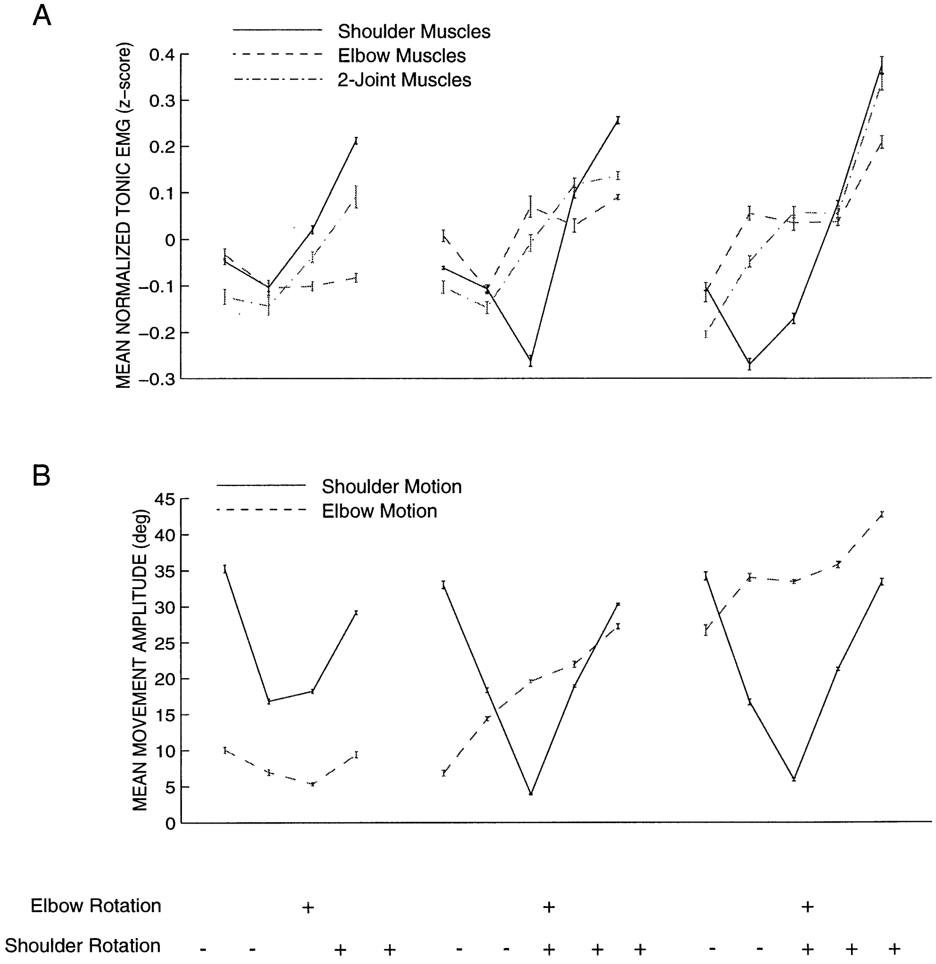

Fig. 2 **A** Mean tonic EMG (averaged over six subjects) as a function of initial limb configuration. EMG activity was normalized using z-scores (see text). *Vertical bars* indicate ±1 standard error. Tonic EMG levels vary with the magnitude of shoulder and elbow movement. **B** Mean shoulder- and elbow-joint movement amplitude (±1 s.e.) as a function of initial limb position. Note that flexions and extensions are both plotted using positive values. The *symbols* along the *absicca* indicate the direction of rotation (+ indicates flexion, – indicates extension)

each initial limb configuration. Figure 2B displays mean values over all subjects. It should be noted that, while shoulder and elbow movement amplitude varied depending on initial limb position, only small variations in the position of the hand at the final target were observed (the average standard deviation was ±16 mm). Moreover, there was no systematic pattern of differences in final hand position across subjects.

To quantitatively assess the relationship between tonic EMG levels after movement and the associated joint rotations during movement, correlation coefficients were computed. Figure 3A shows values for all subjects taken together. Tonic EMG levels of single-joint shoulder muscles were strongly correlated with the amplitude of shoulder rotation ($P<0.01$) and not correlated with the amplitude of elbow rotation ($P>0.01$). In contrast, tonic EMG levels of elbow and double-joint muscles were both strongly related to the amplitude of elbow rotation ($P<0.01$) and not correlated with the amplitude of shoulder movement ($P>0.01$). Thus, for this set of movements, tonic EMG activity of shoulder muscles reflects the amplitude of preceding shoulder movement, while tonic EMG activity of elbow and double-joint muscles reflects the amplitude of elbow movement.

As is characteristic of many movements, maximum velocity varied with movement amplitude. The correlations tested above were thus repeated to examine the relation between tonic EMG and shoulder and elbow peak velocity. The pattern of correlations for movement velocity was the same as that described above for movement amplitude – shoulder EMG varied with peak shoulder velocity, and elbow and double-joint EMG varied with peak elbow velocity. While the present data do not allow a decomposition of the specific relationships between tonic EMG, movement amplitude and velocity, both analyses support the conclusion that there is independent coactivation of shoulder and elbow muscles.

The calculations were also repeated using data from a control study, in which tonic EMG levels at the elbow were calculated using the brachioradialis instead of the biceps long head. The overall pattern of results was similar. Tonic EMG of shoulder muscles was correlated with the amplitude of shoulder motion ($P<0.01$) and not with the elbow motion ($P>0.01$). In addition, tonic activity in single-joint elbow and double-joint muscles was related to elbow motion ($P<0.05$) and not to shoulder motion ($P>0.05$).

To further test the role of the biceps long head, correlations were computed on a per-subject basis between tonic activity in biceps long head and brachioradialis (a single-joint elbow flexor). Obtained values ranged from 0.68 to 0.96, with an average of 0.77 ($P<0.01$ in all cases). Thus, the biceps long head and brachioradialis behave similarly with regard to their patterns of tonic

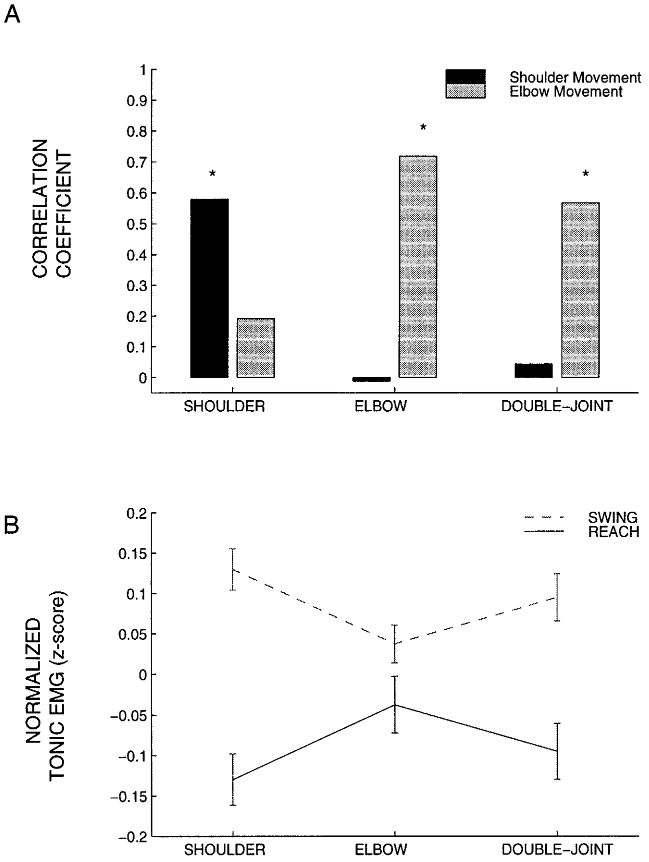

Fig. 3 **A** Correlation of tonic EMG activity with the amplitude of shoulder and elbow movement for all subjects taken together. * indicates that the correlation coefficient is significantly different from zero ($P<0.01$). Tonic EMG activity in single-joint shoulder muscles is correlated with shoulder motion and not with elbow movement, while tonic EMG activity of single-joint elbow and double-joint muscles are both related to elbow motion and not to shoulder movement. **B** Mean tonic EMG activity (±1 s.e.) for movements in which the shoulder and elbow rotate in the opposite direction (*REACH*) and in the same direction (*SWING*). The variance in tonic EMG activity associated with differences in joint-movement amplitude was first removed using linear regression. The resulting tonic EMG levels in all muscles were significantly higher for SWING movements than for REACH movements

EMG activity at the elbow. Moreover, tonic activity in the biceps long head alone was correlated with the amplitude of elbow motion ($P<0.01$) and not with the amplitude of shoulder motion ($P>0.01$). These tests support the idea that, for the movements tested in this experiment, the biceps long head acts primarily at the elbow and plays a limited role at the shoulder.

The data shown in Fig. 2A indicate that tonic EMG levels after movements in which the shoulder and elbow joint rotated in the same direction (swinging movements) may be higher than tonic EMG after movements in which the joints moved in opposite directions (reaching movements). To assess this possibility, differences in tonic EMG levels for reach and swing movements were examined after the variance in EMG levels due to differences in movement amplitude was removed. This enabled us to assess whether factors other than movement amplitude contributed to tonic EMG levels in reach versus swing movements. For each muscle, a linear function relating shoulder and elbow joint movement amplitude to tonic EMG activity was computed by regression on a per-subject basis. This function was then subtracted from tonic EMG scores, and the resulting values were divided into two groups: those associated with swinging movements and those associated with reaching movements. This procedure is equivalent to an analysis of covariance, in which movement direction (reach or swing) is the independent variable, tonic EMG the dependent variable and movement amplitude is treated as a covariate. These data are shown in Fig. 3B. Tonic EMG levels for all muscles were higher after swinging movements than those after reaching movements ($P<0.01$ for shoulder and double-joint muscles, $P<0.05$ for elbow muscles).

In order to assess interaction torques at the shoulder and elbow during swing and reach movements, the velocity-dependent terms in the forward dynamics equations were computed for all subjects (Hollerbach and Flash 1982). Elbow-interaction terms were computed as the square of shoulder velocity, and shoulder interaction terms were computed as the squared elbow velocity plus the product of the shoulder and elbow velocities. The maximum values of shoulder interaction terms were on average 6.5 times larger in swing movements than in reach movements ($P<0.01$). In contrast, there were no differences between the maximum values of the elbow interaction terms ($P>0.01$).

Discussion

Following movements to a single target, tonic EMG activity varied as a function of the magnitude of shoulder and elbow motion. These differences in tonic EMG activity occurred as a natural accompaniment of multijoint movement. No specific instructions were required in order to elicit these patterns of coactivation.

For the movements tested here, tonic activity of single-joint shoulder muscles was strongly related to shoulder motion and not to elbow movement, while the tonic activity of elbow and double-joint muscles was related to elbow motion and not to shoulder movement. Shoulder muscle co-activation was thus independent of the co-activation of elbow and double-joint muscles. In addition, tonic activity was higher after movements in which the joints moved in the same direction (and interaction torques at the shoulder were high) than after movements in which the joints rotated in opposite directions (and interaction torques at the shoulder were low). The nervous system may thus use muscle coactivation to counteract the effects of forces arising at the shoulder due to multi-joint dynamics.

The idea that there are neural control signals for muscle co-activation has been supported by behavioral and electrophysiological studies (see Introduction) and has also been explored in the context of mathematical models of limb-movement control. The postulation of separate commands for movement and co-activation is a central facet of various versions of the equilibrium-point control hypothesis (Hogan 1985; Flash 1987; Feldman and Levin 1995).

While co-activation and movement may be independently specified (for example in the maintenance of a posture), the present findings suggest that the magnitude of co-activation varies with movement amplitude and velocity. A similar conclusion about the relationship between muscle co-activation and movement velocity was reached in a recent modeling study of single-joint elbow movements. Gribble et al. (1998) report that when the magnitude of muscle co-activation is increased in proportion to peak movement velocity, elbow stiffness during simulated single-joint elbow movements matched values reported in a comparable empirical study (Bennett 1993).

Although it may be desirable to examine muscle co-activation during motion of the limb, examination of co-activation during movement is problematic because of the difficulty of separating aspects of muscle activation due to the control of joint impedance from activity related to force generation for movement and activity arising from reflexes. The use of a detailed neurophysiological model of limb movement which includes these elements (for example, Prochazka et al. 1997; Gribble et al. 1998; Loeb et al. 1998) may be useful to facilitate this separation.

A number of unresolved issues may be noted. In this preliminary examination, subjects performed relatively naturalistic movements, in which movement amplitude and velocity tended to co-vary. In addition, the tests were limited to a single location in the center of the workspace. It is necessary to assess the dependence of tonic EMG on velocity and amplitude separately and to examine the generality of the relationship in different areas of the workspace. Additionally, to link the present findings with the literature concerning limb impedance in statics, it would be useful to know how the changes in tonic EMG levels reported here relate to corresponding changes in joint impedance at the shoulder and elbow. Some evidence related to this issue, in the context of an isometric force-adjustment task, has been reported by Gomi and Osu (1996) and Flash and Gurevich (1997). Similarly, McIntyre et al. (1996) suggest a possible role for co-activation of double-joint muscles in the context of end-point impedance control.

It should also be noted that, in the present experiments, the arm was not supported against gravity. Thus, there was presumably a component of the observed tonic EMG activity in shoulder muscles resulting from holding the limb against gravity. Hence, some of the reported co-contraction is due to the requirements of static equilibrium. However, for the same final position of the limb, tonic activity at the shoulder and elbow changed in a systematic manner with characteristics of the preceding movement. Thus, while a component of tonic activity opposes the gravitational force, the observed changes in tonic activity cannot be accounted for by this alone.

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