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RESEARCH NOTE

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# Persistence of inter-joint coupling during single-joint elbow flexions after shoulder fixation

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**Abstract** Single-joint elbow flexions are associated with muscle activity at the shoulder that opposes interaction torques arising from rotation of the elbow. We have previously shown that this activity is linearly related to elbow muscle torque and is robust in the presence of novel dynamic loads. Here we examined this relationship in the context of shoulder joint fixation. We tested the hypothesis that after mechanically fixing the shoulder the relationship between shoulder muscle activity and elbow muscle torque will be preserved. In contrast, proposals in which energetic variables are optimized predict that shoulder muscle activity should cease. Subjects performed single-joint elbow flexions in a horizontal plane while interacting with the KINARM robotic exoskeleton. After repeated movements with the shoulder joint fixed we observed a slight and gradual decrease in the activity of pectoralis major relative to movements in which the shoulder was free to rotate. However the strength of the coupling between the shoulder and elbow did not change after shoulder fixation. This is consistent with our previous findings and suggests that the nervous system maintains this inter-joint coupling relationship even when activity at the fixed joint is no longer needed for movement accuracy.

**Keywords** Human · Arm movement · Electromyography · Interaction torque · KINARM · Motor learning

## Introduction

Single-joint movements (e.g. at the elbow) require the active control of multiple segments, because of the effects of interaction torques that arise at adjacent “non-focal” joints (e.g. the shoulder) (Hollerbach and Flash 1982). By mechanically fixing the shoulder joint and preventing shoulder rotation, one can eliminate the need to oppose interaction torques with active muscle contraction. Muscle activity typically observed at non-focal joints during single joint movements (Almeida et al. 1995; Latash et al. 1995; Gribble and Ostry 1999; Koshland et al. 2000; Scheidt et al. 2000; Galloway and Koshland 2002) would no longer be needed, and would have no effect on the resulting movement.

Recent studies that examined muscle activity patterns during joint fixation obtained somewhat mixed results. Little or no reduction in muscle activity at mechanically fixed joints was observed during single-joint elbow movements after shoulder fixation (Almeida et al. 1995) or during multijoint reaching movements with wrist fixation (Koshland et al. 2000). Scheidt et al. (2000) reported reductions in muscle activity of the posterior deltoid and triceps brachii long head during elbow flexions with shoulder fixation.

Although previous studies have examined the general effects of joint fixation on movement kinematics and muscle-activity patterns, the relationship between muscle activity at focal and non-focal joints has not been addressed. During unconstrained single-joint elbow flexions, muscle activity at the shoulder joint is linearly related to elbow muscle torque (Gribble and Ostry

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1999). We recently reported that this relationship is robust even in the presence of externally applied loads (Debicki and Gribble 2004). The purpose of the current study was to test the hypothesis that when the shoulder is mechanically fixed, this coupling relationship between the shoulder and elbow is preserved. In contrast, models centered around energetic optimization principles (Uno et al. 1989; Kawato et al. 1990; Nakano et al. 1999; Wada et al. 2001) predict that muscle activity at a mechanically fixed joint would decrease, because it is no longer needed for movement accuracy and is energetically expensive.

## Methods

### Subjects

Six subjects (5 male and 1 female) were tested. Subjects were 21–25 years old (mean age 23.3 years). Subjects were right hand dominant for writing and did not report any neurological or musculoskeletal impairment. The study was approved by the University of Western Ontario Ethics Review Board and all subjects gave informed consent.

### General procedures

Procedures were similar to those described by Debicki and Gribble (2004). Subjects were asked to produce planar arm movements (single joint elbow flexions) while interacting with KINARM, a robotic exoskeleton attached to their right upper limb (Scott 1999; Gribble and Scott 2002). Movements were confined to a horizontal plane and consisted of joint rotations around vertical axes at the shoulder and elbow. A customized clamp was attached to the KINARM linkage joint corresponding to the shoulder joint. Once tightened, this linkage joint (and thus the subject's shoulder joint) was fixed in place. The elbow remained free to rotate.

Subjects performed single-joint elbow flexions (40°) to targets located on a glass tabletop. The orientations of the shoulder and elbow were 30° and 60° respectively (outside angles) at the starting location. Subjects were asked to complete 175 movements, grouped into two blocks: an initial "shoulder free" block (25 trials) and a "shoulder fixation" block (150 trials). Subjects were asked to maintain a peak elbow joint velocity between 230 and $280° \text{ s}^{-1}$. Movement speed was monitored on a trial-to-trial basis by the experimenter who asked subjects to speed up or slow down if the target velocity was not met.

### Signal recording

Shoulder and elbow joint angles were obtained from KINARM motor encoders. Surface electrodes (Delsys) were used to record electromyographic activity (EMG) of shoulder and elbow muscles. Positions and EMG signals were sampled at 1,000 Hz and recorded on a computer. EMG signals were recorded from seven muscles: pectoralis major (clavicular head), posterior deltoid, biceps brachii (long and short heads), brachioradialis and triceps brachii (lateral and long heads). Electrodes were positioned using anatomical landmarks. To minimize the risk of cross-talk, electrode placements were verified using isometric and movement tests (Gribble and Ostry 1999).

### Data analysis

Positions were low-pass filtered at 15 Hz using a second-order Butterworth filter implemented in Matlab (The Mathworks). Filtered positions were differentiated using a central difference algorithm to obtain joint velocities. Movement onset and end were defined as the times at which elbow velocity crossed a threshold of $5° \text{ s}^{-1}$.

Electromyographic data were band-pass filtered (30–300 Hz), full-wave rectified, and then low-pass filtered (15 Hz). To compare EMG across different movement conditions the mean amplitude of phasic muscle activity across a fixed time-window was computed. For agonist muscles (pectoralis major, biceps brachii, and brachioradialis) this time window was $-100$ ms to $+100$ ms centered around movement onset. This window was chosen to capture the agonist burst of EMG activity for flexor muscles at the shoulder and elbow. Mean EMG was normalized using *z*-scores (Gribble and Ostry 1999). Means were normalized separately for each muscle and each subject. As a control, mean EMG was also normalized as a percentage of maximum observed EMG across the experiment, for each subject and each muscle. The results were qualitatively similar using both normalization methods.

Elbow muscle torque was computed using inverse-dynamics equations described previously (Debicki and Gribble 2004). Because the fixation clamp absorbed all active and passive torques at the shoulder, muscle torques during shoulder fixed trials could not be computed at the shoulder. Elbow muscle torques were normalized using *z*-scores. This enabled us to assess the relationship between shoulder muscle activity and elbow torque using similar units. Normalization of elbow torques also helped to control for slight variations in peak elbow-joint velocities across different subjects. Statistical tests were carried out using single-factor repeated-measures analysis of variance (ANOVA). Linear regression was used to test the relationship between shoulder EMG and elbow muscle torque.

## Results

Figure 1b shows time-varying joint positions, velocities, and muscle-activity patterns for movements in the shoulder free and at the end of the shoulder fixed

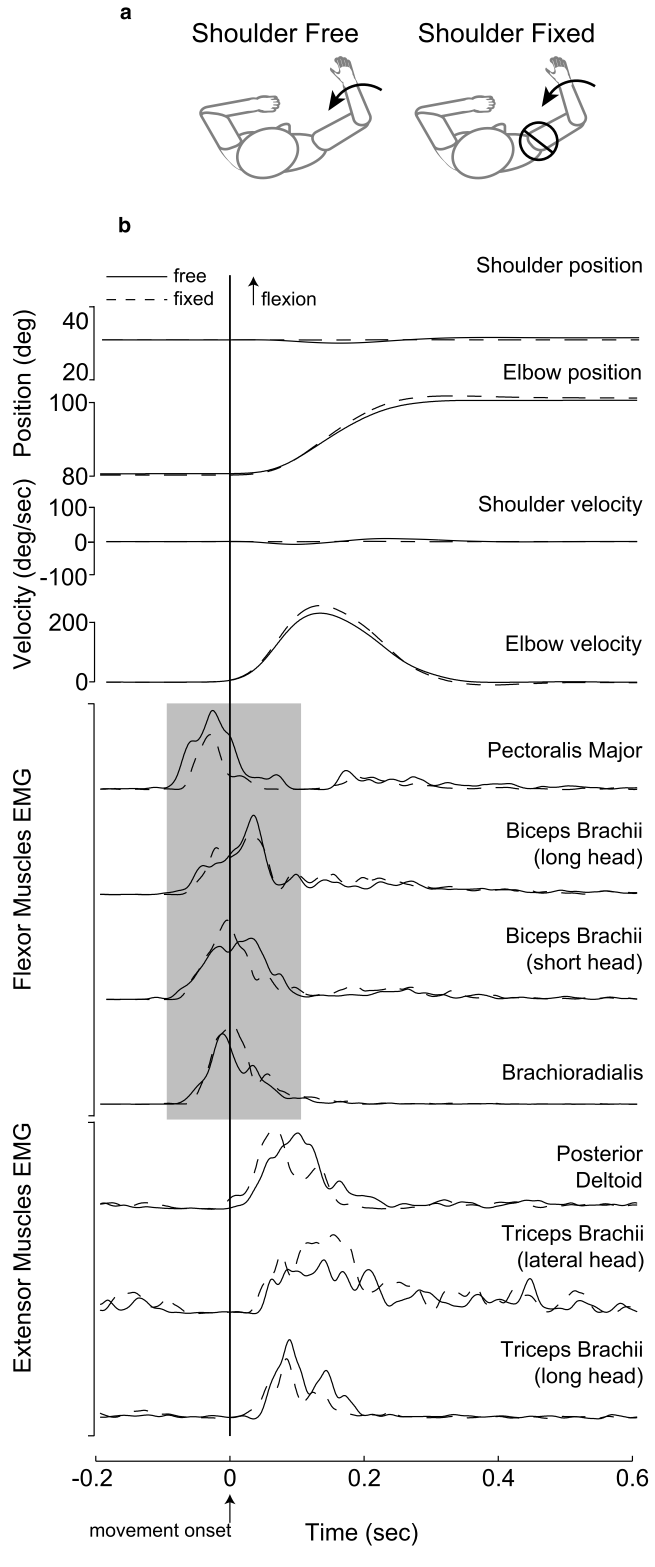

**Fig. 1** Time-varying joint positions, velocities and EMG recordings for a representative subject during elbow flexion movements in shoulder free and shoulder fixed conditions. **a** Subjects performed single-joint elbow flexions (constrained to the horizontal plane). The shoulder was either free to rotate or mechanically fixed in position by means of a clamp attached to the KINARM. **b** Each trace represents the mean of the last ten trials in the initial shoulder free condition (*solid line*) and the mean of the last ten trials in the shoulder fixed condition (*dashed line*). All signals are aligned to movement onset (*solid vertical line*). Positive joint angles indicate movements in the flexion direction. The *shaded area* indicates the time window used to calculate mean agonist EMG for flexor muscles

conditions (shown schematically in Fig. 1a). Data shown are for a single representative subject. During the shoulder free trials the shoulder remained essentially stationary, and during fixation all shoulder motion was eliminated. Elbow kinematics remained the same as in the shoulder fixed movements.

The onset of elbow flexion was preceded by phasic EMG at both shoulder and elbow flexor muscles. Extensor muscles were quiescent until just after movement onset. A small decrease in EMG was observed in the pectoralis major (a shoulder flexor muscle) during the shoulder fixed condition relative to the shoulder free condition. Extensor muscles were more variable and no reliable changes in EMG were observed except for triceps brachii (lateral head), which showed a small increase in activity with shoulder joint fixation.

To quantify changes in EMG as a result of shoulder fixation, mean EMG was computed during fixed time windows (see "Methods" and Fig. 1b). In the analyses that follow we examine the initial feed-forward component of movement control and thus focus on agonist muscles. Analysis of antagonist muscles was not undertaken because of the potential influences of afferent feedback or voluntary corrections that may occur later in movement (e.g. after 100 ms from movement onset). Figure 2a shows mean normalized pectoralis EMG for all movements in the shoulder free and shoulder fixed conditions. There was a small and gradual decrease in pectoralis EMG over the course of the shoulder fixed movements. Brachioradialis and biceps (long and short heads) showed no significant changes with shoulder fixation. No reliable changes in elbow velocity were seen during shoulder joint fixation.

Repeated-measures ANOVA was used to test for differences between mean EMG for the shoulder free condition and the end of the shoulder fixed condition. We only observed a statistically significant decrease in muscle activity for the pectoralis from the shoulder free to the end of the shoulder fixed condition ($P < 0.05$, Fig. 2b). The mean decrease relative to the shoulder free movements corresponds to 28.1% when EMG was normalized to maximum observed EMG over the experiment (see "Methods"). No significant changes in mean EMG were observed for brachioradialis or biceps long and short heads ($P > 0.05$). There were no significant changes in peak elbow muscle torque or peak elbow joint velocity ($P > 0.05$).

To test for possible changes in inter-joint coupling patterns we examined the relationship between shoulder muscle activity and elbow muscle torque. We took advantage of the trial-to-trial variability in elbow velocity (and hence elbow muscle torque) to examine the

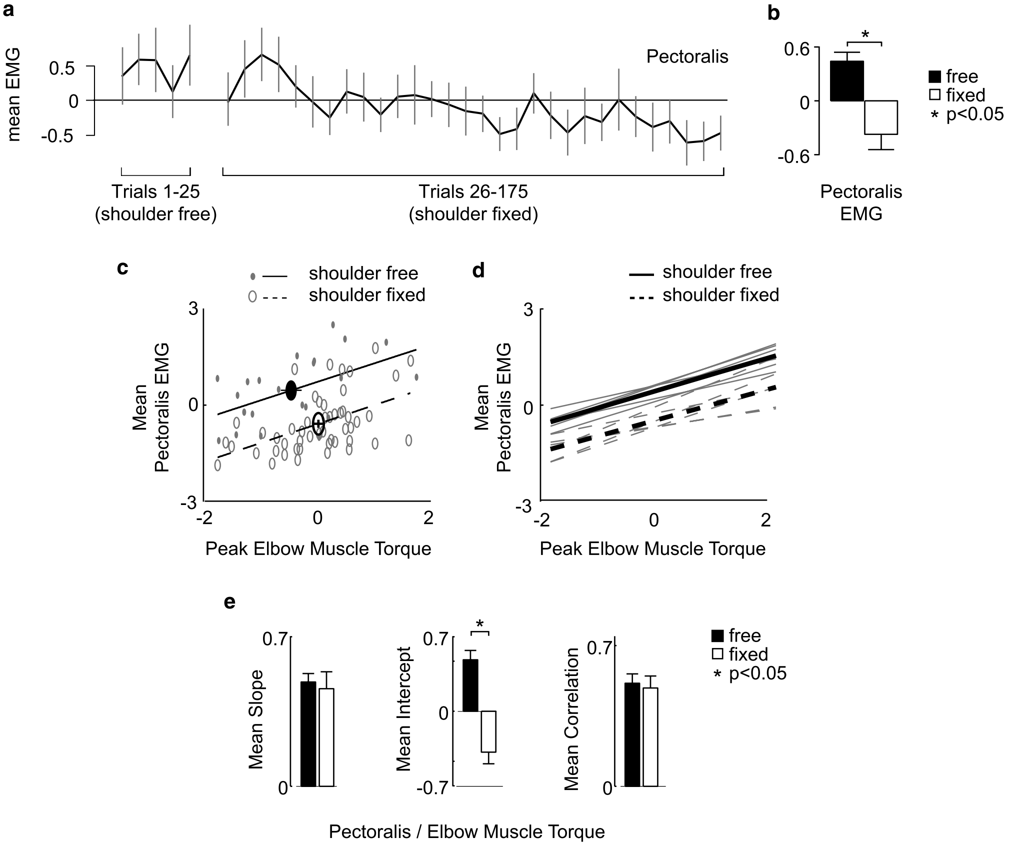

**Fig. 2** **a** Normalized mean pectoralis EMG for shoulder free and shoulder fixed movements. Data points represent the mean of five consecutive movements. *Vertical lines* represent one standard error averaged across subjects. **b** Mean normalized pectoralis EMG for 25 shoulder free movements (*solid bars*) and the last 25 shoulder fixed movements (*open bars*). **c** Relationship between normalized mean pectoralis EMG and elbow muscle torque for shoulder free (*closed circles*) and shoulder fixed (*open circles*) movements. Data are for a single representative subject. Linear regression lines of best fit are shown for shoulder free (*solid line*) and shoulder fixed (*dashed line*) movements. **d** Mean linear regression lines of best fit for all subjects in shoulder free (*solid lines*) and shoulder fixed (*dashed lines*) movements. *Thick lines* represent mean data averaged across all subjects. **e** Mean slope, intercept, and correlation coefficients for shoulder free (*filled bars*) and shoulder fixed (*open bars*) movements. *Vertical bars* indicate one standard error of the mean

relationship between pectoralis EMG and elbow muscle torque. Mean peak elbow velocity across subjects was 291.4° $s^{-1}$ (SD = 34.1° $s^{-1}$). Mean peak elbow muscle torque was 18.8 Nm (SD = 3.8 Nm). We used data from the last 50 movements in the shoulder fixation condition in the analyses that follow.

Figure 2c shows the relationship between pectoralis EMG and elbow muscle torque for a single representative subject. No changes are seen in the slope of the relationship for shoulder fixed movements compared with shoulder free movements. During both shoulder free and shoulder fixed movements pectoralis EMG varied in the same proportions as elbow muscle torque. In both cases a significant linear relationship was observed ($P < 0.05$, see Fig. 2e). A decrease can be seen in the $y$-intercept of the regression line for shoulder fixed compared with shoulder free movements. Across subjects a similar trend emerged. Figure 2d shows regression lines for all subjects (thin lines) and the mean regression lines across subjects (thick lines). Again, a decrease in the intercept but no change in slope is seen.

As a control we also assessed the relationship between elbow muscle activity and elbow muscle torque. As in previous reports a strong linear relationship was observed between biceps brachii (long and short heads) and brachioradialis EMG and elbow muscle torque ($P < 0.05$ in all cases). No changes in slope or intercept were seen between the shoulder free and shoulder fixed conditions.

Repeated-measures ANOVA was used to test for differences between mean slope and intercept for the shoulder free and shoulder fixed conditions (Fig. 2e). No significant differences between slopes of regression lines were observed for pectoralis ($P > 0.05$). A statistically significant decrease in the $y$-intercept was observed ($P < 0.05$). No differences were observed in slope or intercept for brachioradialis or biceps (long and short heads) ($P > 0.05$ in all cases).

We also tested the relationship between shoulder muscle activity and elbow muscle torque by computing Pearson product–moment correlation coefficients. For all subjects, statistically significant correlations were observed for both the shoulder free and fixed conditions, for pectoralis, biceps brachii (long and short heads), and brachioradialis ($P < 0.05$). In addition we tested for differences in correlation between the shoulder free and fixed conditions. No changes in mean correlation were observed between shoulder free and fixed conditions ($P > 0.05$ for pectoralis and biceps brachii long and short heads). A statistically reliable decrease in correlation was observed for brachioradialis, nevertheless in both shoulder free ($r = 0.68$) and fixed ($r = 0.48$) conditions both correlations were statistically significant ($P < 0.05$).

## Discussion

We observed a slight and gradual decrease in pectoralis EMG after subjects performed 150 elbow movements with the shoulder fixed. No changes were seen in the relationship between pectoralis activity and elbow movement. We observed no change in the correlation between pectoralis EMG activity and elbow muscle torque, nor a change in the slope of the regression line. Instead, only a decrease in the intercept was observed. Thus, although there was a statistically reliable decrease in mean pectoralis muscle activity, there were no changes in the strength of the relationship between pectoralis activity and elbow muscle torque after shoulder fixation.

This pattern of results is not consistent with proposals in which energetic variables such as muscle torque, muscle torque change or commanded muscle torque are minimized in order to specify neural control signals for movement (Uno et al. 1989; Kawato et al. 1990; Koshland et al. 2000; Wada et al. 2001). Models such as these would predict that because shoulder motion (and hence the effects of joint interaction torques due to motion of the elbow) has been eliminated and muscle activity at the shoulder is no longer required to prevent shoulder motion, active contraction of shoulder muscles, which is energetically expensive, should cease. Our results suggest that there was some gradual change in the descending motor command to pectoralis major after repeated movements with the shoulder fixed. However, the observed decrease in pectoralis activity did not follow the short time course of adaptation typically observed in studies involving sudden changes in movement dynamics (Shadmehr and Mussa-Ivaldi 1994). In contrast, the changes observed here and in other studies of joint fixation (Scheidt et al. 2000) were gradual and incomplete.

One possibility is that rapid changes to neural control signals for movement are driven primarily by kinematic error (Scheidt et al. 2000). Information about kinematic error may be provided by afferent signals such as those originating from muscle spindles and cutaneous afferents (Sainburg et al. 1995). When a joint is mechanically fixed, superfluous muscle activity at that joint has no effect on limb position. Kinematic error would not be present. With immobilization, isometric contractions would occur and hence there would be atypical muscle spindle feedback from shoulder and biarticular muscles in comparison with the shoulder free condition. This atypical feedback may drive the observed gradual reduction in shoulder EMG. Complete cessation of pectoralis activity and/or a dissociation between the control of shoulder and elbow muscles may occur after significantly more training (e.g. multiple training sessions over several days) however no such tests have been reported.

Our results suggest that the nervous system preserved the relationship between the control of shoulder and elbow muscles after joint fixation. Mechanisms that exist during natural free motion to generate muscle activity at the shoulder in order to oppose joint interaction torques arising from elbow motion were still active after repeated movements with the shoulder joint fixed. We have shown previously that this inter-joint coupling relationship is robust even in the face of movement-dependent loads (Debicki and Gribble 2004). These results taken together suggest that in the absence of kinematic error the neural mechanisms that underlie compensation for joint interaction torques may be particularly resistant to adaptation. Moreover the persistence of inter-joint coupling suggests that muscle activation may occur at non-focal joints in any single-joint task. Thus single-joint movements can be viewed as a special case of multi-joint movement.

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