Changes in wrist muscle activity with forearm posture: implications for the study of sensorimotor transformations

Aymar de Rugy,1 Rahman Davoodi,2 and Timothy J. Carroll1
1Centre for Sensorimotor Neuroscience, School of Human Movement Studies, The University of Queensland, Brisbane, Queensland, Australia; and 2Department of Biomedical Engineering, University of Southern California, Los Angeles, California

Submitted 14 February 2012; accepted in final form 6 September 2012

Changes in wrist muscle activity with forearm posture: implications for the study of sensorimotor transformations. J Neurophysiol 108: 2884–2895, 2012. First published September 12, 2012; doi:10.1152/jn.00130.2012.—The primate wrist is an ideal model system for studying the reference frames in which movements are coded within the central nervous system, as a simple rotation of the forearm allows dissociation between extrinsic and body-referenced coordinates. Important information regarding coordinate frame transformations has been obtained using this system, particularly from studies involving extracelluar cortical and spinal recordings from monkeys. Because preferred directions of muscle use were reported to rotate by less than half of the joint rotation, the system was considered to dissociate three reference frames: extrinsic (direction of movement in space), muscle (activity of muscles), and joint (angle of the wrist joint). However, given the relatively minor changes in reported muscle biomechanics with human forearm rotation, the reported distinction between joint space and muscle space is surprisingly large. Here, we reassessed patterns of wrist muscle activity with changes in forearm posture in humans, during an isometric force-aiming task with a device that enabled stringent control of the musculoskeletal configuration. Results show that the preferred directions for wrist muscle activation closely follow forearm orientation (i.e., by 88%). Control experiments confirmed this, whether the hand was clamped passively by a device or grasped a handle. Furthermore, the remaining 12% discrepancy between intended changes in wrist orientation and muscle use also occurred for muscle-pulling directions obtained by intramuscular electrical stimulation. The findings prompt reconsideration of data based on the previously reported dissociation between joint space and muscle space and have critical implications for future investigations of sensorimotor transformations and their adaptation using the wrist.

motor control; muscle redundancy; reaching movements; biomechanics; sensorimotor transformation

COORDINATION AT THE WRIST has been extensively studied in recent decades because it presents classical challenges of motor control, such as muscle redundancy, in a single joint system with a manageable number of muscle actuators and degrees of freedom (Fagg et al. 2002; Fetz et al. 1989; Haruno and Wolpert 2005; Hoffman and Strick 1990, 1993, 1999; Kakei et al. 1999; Kakei et al. 2001, 2003; Raphael et al. 2010; Shah et al. 2004; Yanai et al. 2008). For instance, recent optimal control theories that posit that the nervous system solves muscle redundancy by minimizing costs such as muscle effort or motor noise (Todorov 2004; Todorov and Jordan 2002) were able to qualitatively reproduce the pattern of muscle activation at the wrist (Diedrichsen et al. 2010; Fagg et al. 2002; Haruno and Wolpert 2005). More specifically, the pattern of muscle activity that achieves task goals while minimizing the sum of each muscle’s activity level squared reproduced the cosine-like changes observed in muscle activity with target direction (i.e., the muscle-tuning curve), as well as the known difference between the direction at which a muscle mechanically pulls (i.e., its pulling direction) and the direction at which it is preferentially used (i.e., the muscle-preferred direction, extracted from its tuning curve) (Fagg et al. 2002; Todorov 2002; but see de Rugy et al. 2012 for an argument against online optimization of muscle activation).

Another crucial feature of the wrist is that it can operate in different forearm supination/pronation orientations, which offers several opportunities to experimentalists. For example, simple forearm rotation dissociates extrinsic space from the joint space. It has also been reported that forearm rotation allows dissociation between joint space and muscle space, as muscle-tuning curves rotated to a lesser extent than the forearm. For instance, nonhuman primate studies reported that, as the forearm was rotated by 180° between supination and pronation, the preferred directions for wrist muscle activation rotated by less than half of the joint rotation (range 46–90°, Kakei et al. 1999; Kakei et al. 2001). This dissociation between three major reference frames, when coupled to cortical and spinal recordings, generated information that has been highly influential for our understanding of how movement is coded within the nervous system (Kakei et al. 1999; Kakei et al. 2001; Yanai et al. 2008).

Given the relatively minor changes in reported muscle biomechanics with human forearm rotation, however, the reasons behind the apparent dissociation between joint space and muscle space with posture changes at the wrist is unclear. For instance, changes in human muscle-pulling directions in joint space expected from cadaveric experiments for a 160° forearm rotation are only of the order of 0–10° (Horii et al. 1993; Loren et al. 1996). Here, we reassessed this issue of dissociation between joint space and muscle space at the wrist for human subjects during an isometric force-aiming task performed in an experimental device that enabled a stringent control of the musculoskeletal configuration. The device has multiple adjustable contact points designed to precisely fit the participant’s hand and forearm and thereby isolate force at the wrist. Recordings from the five main wrist muscles were made through fine-wire electrodes inserted directly into muscles, and muscle-pulling directions were determined by electrical stimulation through
the recording wires in a subsample. Results confirmed small, but significant, changes in muscle activity that parallel the minor changes in muscle biomechanics that have been reported to occur with posture, but also revealed that any differentiation between joint space and muscle space is more limited in humans than previously reported in monkeys. By accurately quantifying changes in muscle use with forearm posture, these results prompt reconsideration of previous data and provide a necessary basis for further exploration of the mechanisms by which the nervous system tunes motor commands to the musculoskeletal configuration.

MATERIAL AND METHODS

Subjects. Seven subjects (6 men and 1 woman, aged 23–45 yr) volunteered for this experiment. All subjects were right-handed with normal or corrected-to-normal vision. They all gave informed consent prior to the experiment, which was approved by the local ethics committee and conformed to the Declaration of Helsinki.

General experimental procedure. Subjects sat 80 cm from a computer display positioned at eye level. The right hand was maintained in a custom-made manipulandum with the forearm in one of five possible positions between 80° pronation and 80° supination (i.e., −80°), in steps of 40° (see example of three intermediate positions displayed in Figure 1). The elbow was kept at 110° with the forearm parallel to the table and supported by a custom-built device similar to that used in a previous study (de Rugy and Carroll 2010). The wrist was fixed by an array of adjustable supports, contoured to fit the hand at the metacarpal-phalangeal joints (12 contacts) and the wrist just proximal to the radial head (10 contacts). This allowed wrist forces to be applied without the need for a gripping force. Wrist forces were recorded using a 6-df force/torque transducer (JR3 45E15A-I63-A400N60S, Woodland, CA) coupled with the wrist manipulandum.

Real-time visual feedback of wrist forces was presented on the visual display. Targets were presented at 16 radial positions around the center of the display (i.e., 22.5° apart). In the neutral position, flexion/extension corresponded to the horizontal axis (flexion left), and radial/ulnar deviation corresponded to the vertical axis (radial deviation up). In the four other rotated forearm postures, the visual feedback was rotated with the forearm such that the movement of the cursor matched the force direction in external space (e.g., in 40° pronated posture, a wrist extension produces an upward and rightward movement of the cursor).

A block of 32 maximum voluntary contraction trials was first conducted for each subject with the forearm in the neutral posture. This block was used to normalize the activity of each muscle during the aiming task to the maximal EMG obtained in that muscle during maximum voluntary contraction toward any target direction. Each of the 16 target directions was presented twice in a randomized order. For each direction, subjects were asked to quickly raise their force to the maximal extent while maintaining the force direction within a delineated range of ±8° of target direction. Maximal forces were held for ~2 s. Fifteen seconds were allowed for rest before the next target appeared in another direction.

To obtain muscle-tuning curves in each of five postures, five blocks of 96 trials (6 trials for each of the 16 target directions) were conducted in which a low level of force (i.e., 22.5 N) was required to reach targets. This level of force was identical across all subjects, and it was chosen to reduce the possibility of fatigue. Each trial began only if the cursor was maintained less than 5% of the target distance from the origin continuously for 200 ms. The origin was calibrated to zero force along both axes (wrist relaxed) prior to each block. A random fore period (1–2 s) elapsed before a single target appeared coincident with a brief tone. Participants were asked to move the cursor to the target with a movement time of between 150 and 250 ms, defined as the time between 10% and 90% of the radial distance to the target, and to hold the cursor continuously for 1 s within the target zone (a trapezoid ±8° from target direction by 10% of radial distance to target). A high-pitched tone signaled that the target had been acquired. If the target was not acquired within 2 s of target presentation, a low-pitched tone indicated the end of the trial. A second tone (200 ms after the first) indicated whether the movement time was correct (high tone) or not (low tone), and a bar graph provided visual feedback of the movement time in relation to the prescribed time window. Both the target and cursor disappeared at target acquisition or trial end, and at least 1 s elapsed before the start of the next trial. For each block that corresponded to a given forearm posture, six consecutive trials were conducted for each one of 16 randomly ordered targets. The order of the five blocks that correspond to the five postures tested was also randomized for each subject.

Supplementary experiment 1: hand grasping, wrist constrained. For three subjects who participated in the main experiment, a comparable protocol was repeated after replacing the hand-clamping part of the device used in the main experiment by a handle that required it to be grasped. This manipulation enabled exactly the same level of control over the forearm rotation as in the main experiment. Three experimental blocks similar to those in the main experiment were conducted with both the hand-clamping component and the hand-grasping component in place, one for each forearm orientation (80°, 0°, and −80°). Data were analyzed as in the main experiment. This supplementary experiment was designed to test whether differences with previous studies that involved hand grasping could be attributed to the grasping component of the task.

Supplementary experiment 2: hand grasping, wrist unconstrained. For two subjects who participated in the main experiment, a comparable protocol was repeated after replacing the entire wrist-clamping device used in the main experiment by the hand-grasping device used in de Rugy et al. (2009), which is formed by a bar attached to a 6-df force/torque transducer (Delta ATI, Industrial Automation Systems, Sterling Heights, MI). In contrast to supplementary experiment 1, where the proximal part of the device that constrains the orientation of the wrist was maintained, this device included no such constraints. Both subjects performed experimental blocks similar to those of the
main experiment for each of three orientations of the grasping handle: 90° (pronation), 0°, and −90° (supination).

Based on the observation that subject 1 could only perform the task with substantial mis-rotation of the wrist in relation to the rotation of the handle, we additionally assessed this mis-rotation for subject 2 by measuring the orientation of a light box fitted to the wrist. Because this mis-rotation of the wrist could be affected by the grasping posture, we conducted two additional conditions on subject 2 where the subject was required to maintain a tight grasp of the handle: one in which the body and shoulder posture had to be maintained throughout (two orientations tested at 75° and −75° from neutral), and one in which the body and shoulder posture could be freely adjusted (two orientations tested at 90° and −90° from neutral). These additional conditions were designed to generate different mis-rotations between the wrist and handle, and to test for a possible correlation of this mismatch with the rotation of the preferred direction of muscles.

**EMG procedures.** Electromyographic signals were recorded from extensor carpi radialis longus (ECRl), extensor carpi radialis brevis (ECRb), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), and extensor carpi ulnaris (ECU) muscles, using fine-wire intra-muscular electrodes (75-μm diameter, 2-mm stripped from insulation for recording sites, single wires inserted at 1.5-cm inter-electrode distance). Signals were band-pass filtered from 30 Hz to 1 kHz, amplified 200–5,000 times (Grass P511, Grass Instruments, AstroMed, West Warwick, RI), and sampled at 2 kHz. Electrode locations were determined according to procedures previously reported (Selvanayagam et al. 2011). The insertion point for each muscle was made at a location where the intended muscle had the most superficial muscular structure beneath the skin, and the depth of insertion was regulated to just deep to the first penetration of a muscle fascia (determined by experimenter sensation). All locations were confirmed by asking the subjects to make isolated movements close to the pulling direction of the target muscle and any likely unintended muscle locations. For example, electrode sites for ECRb were confirmed by asking the subject to make weak wrist and finger extension actions. If EMG activity was observed with weak finger extension, the electrodes were removed and new wires were inserted.

**Electrical stimulation of muscles.** A digitimer DS7A medical grade stimulator was used to apply current in short-duration pulse trains (5 pulses at 25 Hz) through the fine-wire recording electrodes to each of the five muscles with the forearm positioned in each of the five postures. The lowest current able to produce a stable isometric force between 5 and 10 N in the neutral posture was used for each muscle (currents ranged between 5 mA and 20 mA; ~2–3 times the threshold current to elicit a force response with a single stimulus). The peak of the force transient was used to indicate muscle-pulling direction. Given the very low stimulus intensity used, the evoked force was likely due to a small number of muscle fibers within the immediate vicinity of the wire. Three stimulus trains were delivered to each muscle in a block at each position in random order, and the series of positions was repeated twice.

**Data reduction and analysis.** Muscle-tuning curves, or the muscular activity as a function of target direction, were determined for each muscle in each posture as the mean rectified EMG during the initial force-ramp phase of the task (i.e., in a time window from 300 ms before to 1,000 ms after force onset) and during the hold-phase of the task (from 100 ms to 100 ms before movement onset to 1,000 ms after). Averaged over five trials to each target (the first of the 6 consecutive trials to each target was discarded to prevent the uncertainty about target direction from contaminating the data), Figure 2 displays examples of this calculation for one muscle (ECRb), and Fig. 3 displays example of muscle-tuning curves determined in joint space (note that the first row is in extrinsic space for illustration) for a subject in the different forearm postures. For each muscle-tuning curve, three main dependent measures were determined: Mdir, the muscle activity summed over the direction of the resultant vector of the tuning curve (Mdir) is indicated for each of these muscle-tuning curves by dashed arrows.
activity summed over all target directions \((M_{\text{sum}})\); 2) the direction of the resultant vector of the tuning curve \((M_{\text{dir}})\), positive angles were measured counterclockwise, starting at wrist extension; this measure reflects the orientation of the resultant vector of the EMG amplitudes at all 16 target directions and was calculated using the command \texttt{circ_mean} of the MATLAB toolbox CircStat for circular statistics as described in Berens (2009); 3) the breadth of the muscle-tuning curve \((M_{\text{bre}})\), which is a transformed version of the muscle activity resultant vector length \((R)\), introduced as an analog of linear standard deviation for circular data \((M_{\text{bre}} = \frac{\text{circ_r}}{\pi})\). In this measure, higher values of \(M_{\text{bre}}\) indicate wider tuning curves. The muscle activity resultant vector length \(R\) was calculated using the command \texttt{circ_r} of the MATLAB toolbox CircStat for circular statistics as described in Berens (2009). Higher value of \(M_{\text{bre}}\) indicates a wider muscle-tuning curve (i.e., less directionally tuned).

To facilitate comparisons between muscles and postures, \(M_{\text{sum}}\) and \(M_{\text{bre}}\) were normalized to values obtained in the neutral posture, and \(M_{\text{dir}}\) was adjusted by subtracting the muscle direction obtained at neutral posture. For each dependent measure and muscle, changes as a function of forearm posture were tested using a one-way repeated-measures ANOVA (5 postures). Changes as a function of the forearm posture were also assessed using linear regressions between the dependent measures and the forearm angle for each subject and muscle. A one-way repeated-measures ANOVA (5 muscles) was conducted on the slopes of the regressions. Sphericity was tested using Mauchly’s test, and the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity when the assumption for sphericity was violated. Differences between slopes obtained for different muscles were also tested using paired-sample \(t\)-tests, and differences from zero were tested using one-sample \(t\)-tests. The significance level was set to \(\alpha = 0.05\), with corrections for multiple comparisons (modified Bonferroni test) conducted following Keppel (1991).

**RESULTS**

Example of general pattern for one subject. Figure 2 displays typical force trajectories and muscle activity obtained for one muscle (ECRb) in two forearm postures \([40° \text{ supination (i.e., } -40°) \text{ to } 80° \text{ pronation in } B]\). This figure indicates that muscle-tuning curves obtained for the initial force-ramp phase and for the stable hold phase were very similar. Given the similarity in the overall pattern of results for both phases, only results from the more stable hold phase of the task are reported. Figure 3 displays all tuning curves obtained for five muscles in five postures of a representative subject. Tuning curves for ECRb are represented in relation to the force direction in external space on the first row for illustration while all other muscle-tuning curves are represented in the joint space (i.e., in relation to wrist direction) in the following five rows. The resultant vectors used for the calculation of \(M_{\text{dir}}\) and the breadth of the muscle-tuning curve \((M_{\text{bre}})\) are indicated by black arrows. FCR, flexor carpi radialis; FCU, flexor carpi ulnaris; ECU, extensor carpi ulnaris.
the apparent increase in FCR activity and the apparent decrease in FCU activity from supinated to pronated postures.

Amplitude of muscle activity. Figure 4A illustrates that $M_{\text{sum}}$ changed with forearm posture for two muscles (i.e., FCR and FCU). The activity of FCR increased from supinated to pronated postures [$F(4,24) = 26.46, P < 0.0005$], and the activity of FCU decreased from supinated to pronated postures [$F(1.26,7.54) = 5.18, P = 0.049$]. Figure 4D also shows that the slopes of regressions conducted on $M_{\text{sum}}$ for the different postures, expressed in proportion of muscle activity at neutral position per degree of forearm rotation, varied between muscles [$F(1.58,9.47) = 10.81, P = 0.005$]. For all comparisons, FCR was the only muscle with a slope that was different from that of every other muscle (all $t > 4.04$, all $P < 0.007$), and that was different from zero ($t = 6.84; P < 0.0005$). FCR decreased its activity by 28% in supination and increased its activity by 40% in pronation relative to neutral. These amplitude changes represent 68% total change in muscle activity from supination to pronation. The slope of FCU was not significantly different from zero, although it approached significance ($t = 2.30, P = 0.061$), and FCU increased its activity by 26% in supination and decreased its activity by 21% in pronation relative to neutral. These amplitude changes represent 47% total change in muscle activity from supination to pronation.

Muscle-preferred direction. Figure 4B shows that the resultant vectors of the tuning curves for all muscles except FCR rotated in relation to the forearm posture (all $F > 12.20$, all $P < 0.003$; cf. individual data provided in Table 1). Figure 4E shows that the slopes that characterize rotations in muscle-tuning curves with forearm postures differed among muscles [main effect for muscle: $F(4,24) = 13.70, P < 0.0005$]. For all pairwise comparisons, FCR was the only muscle for which the slope differed from that of all other muscles (all $t < 2.28$, all $P > 0.062$). The slightly positive slope in FCR represents a mismatch of 4.2° between the rotation of the FCR-preferred direction and the forearm rotation between full supination ($-80^\circ$) and full pronation ($80^\circ$). This contrasts with an average mismatch between muscle-preferred direction and forearm rotation of $-25.1^\circ$ for the four other muscles across the 160° change in posture. The preferred direction of FCR, therefore, rotated differently from that of other muscles by $\sim 30^\circ$. Overall, the average mismatch between the rotation of the preferred direction of FCR and the forearm posture was $-22.9^\circ$.

Fig. 4. Changes with forearm posture of the dependent variables extracted from muscle-tuning curves for all subjects. A, B, and C: $M_{\text{sum}}$, $M_{\text{dir}}$, and $M_{\text{bre}}$, respectively (nu, normalized unit). Positive $M_{\text{dir}}$ indicate angles that are higher than in neutral position, and negative $M_{\text{dir}}$ indicate angles that are lower than in neutral position. D, E, and F: slopes of linear regressions conducted on $M_{\text{sum}}$, $M_{\text{dir}}$, and $M_{\text{bre}}$, respectively. Slopes are expressed in units of the dependent variable per degree of forearm rotation. Error bars indicate standard deviations. S, supinated; P, pronated; N, neutral. *Significant effects ($p < 0.05$).
Table 1. \( M_{mp} \) values for each subject and muscle

<table>
<thead>
<tr>
<th></th>
<th>ECRI</th>
<th>ECRb</th>
<th>FCR</th>
<th>FCU</th>
<th>ECU</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-80^\circ)</td>
<td>6.8</td>
<td>0.7</td>
<td>15.6</td>
<td>9.7</td>
<td>14.0</td>
</tr>
<tr>
<td>(-40^\circ)</td>
<td>8.4</td>
<td>17.0</td>
<td>9.7</td>
<td>14.0</td>
<td>17.2</td>
</tr>
<tr>
<td>(0^\circ)</td>
<td>7.1</td>
<td>13.9</td>
<td>13.9</td>
<td>14.0</td>
<td>17.2</td>
</tr>
<tr>
<td>(40^\circ)</td>
<td>11.2</td>
<td>13.9</td>
<td>14.0</td>
<td>17.2</td>
<td>19.2</td>
</tr>
<tr>
<td>(80^\circ)</td>
<td>11.2</td>
<td>13.9</td>
<td>14.0</td>
<td>17.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Muscle activity summed over the direction of the resultant vector of the tuning curve \( (M_{mp}) \) values are presented for each subject, one line per subject, and for each muscle, for the different postures \((-80^\circ, -40^\circ, 0^\circ, 40^\circ, 80^\circ)\); note that \( M_{mp} \) was not presented at \( 0^\circ \) since it was adjusted by subtracting the direction obtained at neutral posture. ECRI, extensor carpi radialis longus; ECRb, extensor carpi radialis brevis; FCR, flexor carpi radialis; FCU, flexor carpi ulnaris; ECU, extensor carpi ulnaris.

direction of the five muscles (i.e., \(-19.2^\circ\)) and the forearm posture represents 12% less rotation of the muscle-preferred direction than forearm rotation over the range of motion tested (i.e., \(160^\circ\)). This means that, on average, the rotation of muscle use followed the forearm rotation by 88%.

\( M_{bre} \). Increases in the magnitude of \( M_{bre} \) would indicate that a muscle is activated substantially to a wider range of target directions. Figure 4C illustrates that \( M_{bre} \) changes with forearm posture for two muscles only: it increased from supinated to pronated postures for FCR \([F(1,87,11.19) = 13.72, P = 0.001]\) and for FCU \([F(1,77,10.66) = 9.01, P < 0.0005]\).

Figure 4F shows that slopes of linear regression on \( M_{bre} \) as a function of forearm posture varied between muscles \([F(4,24) = 5.088, P < 0.004]\). Slopes were found to be different between ECRI and FCR \((t = 4.26, P = 0.005)\), between ECRI and FCU \((t = 3.15, P = 0.02)\), and between FCR and FCU \((t = 4.03, P = 0.007)\). Slopes of \( M_{bre} \) across postures for FCR and FCU were also found to be different from zero \((t = 4.92; P = 0.003\) for FCR, and \(t = 3.45, P = 0.014\) for FCU). Thus the tuning curves for ECU and FCR became wider as the wrist rotated from supination to pronation.

Muscle-pulling directions determined from electrical stimulation.

Figure 5 displays the pulling directions of the five main wrist muscles determined on four subjects from electrical stimulation of muscles. Figure 5A shows that, at neutral position, these pulling directions (averaged \(77.2^\circ\), \(52.3^\circ\), \(165.5^\circ\), \(233.1^\circ\), and \(304.5^\circ\), for ECRI, ECRb, FCR, FCU, and ECU, respectively) were relatively consistent amongst the four subjects. These directions are also close to the directions of movement elicited by electrical stimulation in nonhuman primates (see Fig. 13 in Hoffman and Strick 1999). Figure 5B additionally shows rotations with forearm posture in the pulling directions of all muscles \((18.5^\circ, 12.9^\circ, 27.1^\circ, 16.7^\circ, 21.5^\circ)\) for ECRI, ECRb, FCR, FCU, and ECU, respectively, with an overall averaged rotation \((-19.3^\circ)\) that is similar to the overall rotation obtained for \( M_{mp} \) in the main experiment \((-19.2^\circ)\). This means that the 12% mismatch between the rotation of the device and changes in muscle-preferred directions corresponds to the mismatch between the rotation of the device and changes in muscle-pulling directions measured by electrical stimulation. Figure 6 also shows that changes in muscle-preferred direction with forearm posture correlated with changes in muscle-pulling direction determined from electrical stimulation on these four subjects \((r^2 = 0.43, P < 0.001)\). These changes in pulling and preferred directions could be due to genuine biomechanical changes and/or to a small rotation of the forearm in the device.

Supplementary experiment 1: hand grasping, wrist constrained.

Figure 7 displays muscle-tuning curves in extrinsic space for one subject, either with the hand-clamping component of the original device replaced by a grasping handle (Fig. 7A), or with the original device (Fig. 7B). This figure shows that muscle-tuning curves rotate from pronated to supinated postures, but also that the amount of rotation and the qualitative pattern of muscle activity are similar for the two conditions. Figure 8 regroups muscle-preferred directions from the three subjects in a format similar to that presented in Fig. 1 in Kakei et al. (1999). When regrouped and compared with the rotation of the device, it appears that muscle-preferred directions follow the rotation of the device similarly for both the hand grasping (Fig. 8B, mean ± SD rotation of 134.5 ± 14.9° from pronated to supinated postures) and the original hand-clamping device (Fig. 8C, mean ± SD rotation of 134.3 ± 10.8° from pronated to supinated postures). Thus, when a similar level of constraint of the forearm rotation is afforded by clamping of the proximal part of the wrist, muscle patterns appear very similar whether...
the task is performed with the hand clamped or grasping a handle.

Supplementary experiment 2: hand grasping, wrist unconstrained. Figure 9 displays data from the two subjects who participated in supplementary experiment 2, which was conducted with a hand-grasping device that did not directly constrain the wrist. Figure 9, B and C, shows apparent (but spurious) dissociations between muscle space and joint space that are qualitatively similar to those reported in primate studies (Kakei et al. 1999; Kakei et al. 2001; Yanai et al. 2008) for both subjects. As the handle of the grasping device was rotated by 180° between the pronated and the supinated postures, the direction for which muscles were preferentially used rotated by approximately half of this rotation (average of 95° and 107° for the five muscles for subject 1 and 2, respectively). However, when wrist orientation was measured for subject 2 when the task was performed with a number of different postures and grasping styles, the maximal 73° mis-rotation between muscle-preferred directions and handle orientation obtained with the least constrained posture was almost completely matched by a 68° mis-rotation of the wrist. When data from the different conditions tested for subject 2 were regrouped, the mis-rotation of the wrist was found to correlate with the mis-rotation of muscle-preferred directions (Figure 10, $r^2 = 0.86, P < 0.01$).

DISCUSSION

Large differences in muscle activity in relation to joint space have been reported previously for primate wrist movements performed in different forearm orientations, but, given the relatively minor biomechanical changes that are expected when the human forearm rotates, these large discrepancies are surprising. Here, we showed that forearm rotation causes small but significant changes in wrist muscle activity that parallel the minor associated changes in muscle biomechanics (Horii et al. 1993; Loren et al. 1996) during an isometric force-aiming task performed with precisely controlled musculoskeletal configuration in humans. However, the apparent mismatch between the changes in preferred directions of muscle activity and joint rotation were substantially smaller than previously reported in monkeys. We found that activation of wrist muscles was almost identical for grasping and hand-clamping when the wrist posture was tightly controlled. Furthermore, the apparent muscle-joint space mismatch was similar to the measured mismatch between wrist and handle orientations. We believe that these results show beyond doubt that the preferred direction of wrist muscle activations closely matches joint orientation for the human subjects we studied. They also illustrate that results qualitatively similar to those obtained in the monkey studies can be obtained if there is a mismatch between joint and handle orientation. While we believe that this type of effect is the most parsimonious explanation for the previous reports of a joint-muscle reference frame mismatch in monkeys, we...
accept that the only irrefutable proof that the monkey results were due to this effect would be to retest the same monkeys with stringent postural control. In the absence of such data, it would seem prudent to interpret the previously reported distinction between muscle and joint space with caution. Our results also provide the necessary baseline to use the wrist system to investigate the mechanisms by which the CNS tunes motor commands to the ongoing posture, and to investigate the reference frame of sensorimotor adaptation.

*Rotation in muscle use closely follows forearm rotation.* A series of influential studies involving invasive recordings from non-human primates have used a wrist-aiming task performed in different forearm orientations to establish the reference frame in which movement direction is coded. Because preferred direction of muscle use was found to rotate by less than half that of a 180° forearm from full pronation to supination (range 46–90°, which corresponds to 25.5–50% of the device rotation, Kakei et al. 1999), this manipulation was considered to dissociate three reference frames for wrist movements: extrinsic (related to the direction of movement in space), muscle (related to the activity of individual or groups of muscles), and joint (related to the angle of the wrist joint) (Kakei et al. 1999; Kakei et al. 2001; Yanai et al. 2008). This dissociation revealed distinct subpopulations of “extrinsic” and “muscle-like” neurons in the primary motor cortex (M1) (Kakei et al. 1999), a population of directionally tuned neurons that are almost exclusively “extrinsic-like” in ventral premotor area (Kakei et al. 2001), and spinal interneurons that follow a reference frame that is more “muscle-like” than that of M1 neurons (Yanai et al. 2008). Our results in humans, however, indicate that the directions for which muscles are preferentially used follow much more closely (i.e., by 88%) the intended rotation of the forearm. Also, for the first time, we determined the pulling directions of the five major wrist muscles in four human subjects by electrical stimulation that was applied to the wrist muscles through the wires used for recording. An overall mismatch between muscle-pulling direction and forearm orientation was found in the direction opposite to that of the intended forearm rotation. The extent of this rotation corresponds to the 12% less rotation of the preferred direction of muscle than the intended forearm rotation, which could be due to genuine biomechanical changes and/or small rotation of the forearm in the device. Given that changes in pulling directions expected from cadaveric experiments for a 160° rotation are of the order of 0–10°, a significant contribution from wrist rotation in the device seems likely (Horii et al. 1993; Loren et al. 1996).
In summary, our isometric force production task at the wrist in different forearm postures did not elicit the clear dissociation between joint space and muscle space reported previously in nonhuman primate studies, but only a small difference that could be partly due to a technical artifact. In fact, this result is more consistent with the relatively minor reported changes in the biomechanical action of wrist muscles in different forearm orientation. For instance, Horii et al. (1993) reported that, from the five major wrist muscles, forearm rotation affected only the moment arm of ECU. Although similarities between human and monkey forearms are not well documented, the origins and insertions of wrist muscles in humans appear to be similar to those of monkeys (Hartman and Straus 1969). It is, therefore, surprising that large differences between muscle and forearm rotations were obtained in previous studies. Our results are also consistent with those of Flanders and Soechting (1990), who showed changes in muscle use that paralleled changes in muscle biomechanics during isometric force performed in different arm postures (see also Buneo et al. 1997). The likelihood that a nonnegligible rotation of the forearm in the device occurred here, despite the relatively tight postural control of the current device, suggests that a larger mismatch with intended forearm rotation might have occurred in the less constrained apparatus used in earlier studies (i.e., which required monkeys to grasp a handle presented in different orientations, Hoffman and Strick 1986). Different grasps, as well as possible rotations of the humerus that might be expected if the posture of the body and arm were not constrained, could have elicited substantial differences between the orientation of the handle and that of the forearm. Although the requirement for grasping implies that finger muscles were involved, which have mechanical actions at the wrist (Gonzalez et al. 1997; Hale et al. 2011), our supplementary data suggest that grasping is unlikely to contribute to major biomechanical changes with forearm orientation. More specifically, we demonstrated in supplementary experiment 1 that, with a similar level of constraint upon the rotation of the wrist and forearm as in the main experiment, hand grasping elicited similar rotation of muscle-preferred direction (Fig. 8). In contrast, we observed an apparent (but spurious) dissociation between muscle and joint reference frames similar to that reported in primate studies, using a less constrained hand-grasping isometric device that did not control for wrist and forearm orientation in supplementary experiment 2 (Fig. 9). Furthermore, we showed for one subject that, when the wrist was unconstrained, the discrepancy between the rotation of the device and that of the muscle-preferred directions corresponded approximately to the mis-rotation between the wrist and device. We did not
seek to rigorously document the relationship between joint and handle orientation for different grips in multiple subjects because the main purpose of the current study was to establish how muscle activation varies with the true joint orientation. We achieved this by constraining the wrist to rotate with the handle, rather than by allowing free posture and correlating changes in joint position with those in muscle-tuning curves. Future studies could take this correlation approach, but the fact that results qualitatively similar to those from the monkey studies were only obtained when there was substantial mis-rotation between the device and the wrist (for two subjects) highlights the possibility that the large dissociation between muscle and joint reference frames observed previously might be attributable to technical artifacts. The results of earlier studies were interpreted as evidence that motor networks code movement details in extrinsic and/or muscle-based references frames, since no population of neurons was found to code the task in joint-based reference frames (Kakei et al. 1999; Kakei et al. 2001; Yanai et al. 2008). Despite the fact that our current data are from humans rather than monkeys, and there may be interspecies differences in biomechanics, these data suggest that previous distinctions between joint- and muscle-based reference frames should be interpreted with caution. Although definitive data are lacking, we suggest that it would be prudent not to exclude the possibility that neurons found to code movements in an intrinsic reference frame could represent motion in joint-based coordinates on the basis of experiments involving the primate wrist.

Small but significant changes in muscle activity with posture. Despite the fact that the orientation of muscle use was found to follow forearm orientation more closely than previously reported over a range of supinated and pronated postures, there were a number of significant changes in muscle activity relative to joint position with posture. For example, there was 1) an increase in FCR activity and a decrease in FCU activity as the forearm rotated from supination to pronation; 2) a rotation in the direction for which FCR is preferentially used that differed from the other muscles; and 3) an increase in the breadth of the muscle activity tuning functions over target directions for FCR and FCU muscles (i.e., a decrease in the precision of their directional tuning). Some of these changes could be related to changes in muscle biomechanics with forearm orientation. For instance, the increase in FCR activity likely reflects the fact that this muscle is shorter in more pronated postures and might therefore operate in a less favorable part of its length-tension curve and require more activation to generate the same force. Providing a specific biomechanical account of the entire pattern of changes in muscle use with posture is, however, complex. One reason is that a muscle cannot be considered in isolation, but must rather be considered in conjunction with other muscles with which its mechanical action is combined. In this context, a change in the activity of a particular muscle does not necessarily reflect a change in the mechanical action of that muscle, but possibly a change in the biomechanics of its neighbors. Irrespective of their relationship with specific changes in limb biomechanics, the differences in muscle activity with posture reported here somehow had to be produced by the central nervous system (CNS). How motor commands are tuned to the ongoing posture is a long-standing question in motor control. Although neurons in M1 were found whose activity parallel changes in muscle activity with limb postures (Sergio and Kalaska 1997, 2003), these changes are likely to be ultimately tuned by feedback integration by lower motor networks (de Rugy et al. 2012; Graziano 2006; Loeb et al. 1999; Yanai et al. 2008). The wrist system appears particularly interesting to investigate these lower-level components, because wrist muscles switch their functional relationship, depending on the direction of action, and the spinal cord circuitry is known to be intimately related to this adjustable functional relationship (Baldissera et al. 2000; Carroll et al. 2005; Pierrot-Deseilligny and Burke 2005; Raphael et al. 2010). For instance, FCR and FCU are synergists for wrist flexion, but antagonists for radial and ulnar deviations. In this context, it would be interesting to establish the origin of the opposite, graded changes in the activity of the partial synergists FCR and FCU reported here with changing postures. The present data set provides, therefore, a useful baseline for further investigation along these lines.

The wrist as a model to investigate reference frames of sensorimotor adaptation. Our results also have important implications regarding the use of the wrist system to investigate the reference frame of sensorimotor adaptation. The pattern of generalization to different areas of the workspace is a widely used paradigm to investigate the substrate of sensorimotor adaptation (Gandolfo et al. 1996; Ghahramani et al. 1996; Krakauer et al. 2000; Shadmehr and Mussa-Ivaldi 1994). However, in the reaching tasks typically used to study generalization to different workspace locations, changing the posture of the limb simultaneously alters motor requirements according
to multiple reference frames. This complicates interpretation, since it is not possible to dissociate between the multiple correlated coordinate systems according to which motor adaptation might be encoded. In this context, isometric force at the wrist collapses complex kinematic and dynamic transformations into the relatively simple relationship between muscle activation and joint force reported here, and generalization of a learned sensorimotor transformation to a different forearm orientation presents the practical advantage that joint- and muscle-based information can be altered, while leaving visual information completely unaffected.

In the literature on sensorimotor adaptation, muscle space and joint space have generally been considered without distinction under the umbrella of an “intrinsic” reference frame. In the case of force-field adaptation, for instance, Gandolfo et al. (1996) found that after-effects were specific to the grip and posture used to hold a manipulandum that applied the force field. This manipulation modified the joint torque as well as the muscle activity required to produce the movement, but not the force experienced at the end effector. On the other hand, successful generalization to an unpracticed area of the workspace has been found repeatedly when the mapping between joint torque and displacement, as opposed to the mapping between endpoint force and displacement, is maintained (Ghez et al. 2000; Malfait et al. 2002; Shadmehr and Mussa-Ivaldi 1994). All of these results were interpreted as supporting an adaptation occurring predominantly in an intrinsic coordinate system, without clear distinction between joint space and muscle space. However, this distinction could be critical, as it was the case for our recent demonstration that at least part of the adaptation to a rotated visual feedback occurs at the level of the final transformation into muscle activation (de Rugy 2010; de Rugy et al. 2009).

To a certain degree, the present study could justify neglecting the distinction between muscle and joint space for adaptation to novel transformations that necessitate changes of an order of magnitude substantially higher than the changes reported here between muscle and joint. However, testing generalization of adaptation to a more subtle transformation, by targeting an area of the workspace for which muscles activity changes with forearm posture are maximal (e.g., between FCR and FCU), has the potential to dissociate muscle space from joint space components of the adaptation.

Conclusion. In sum, the current data illustrate changes in the activity of wrist muscles with forearm posture that 1) questions the previously reported distinction between joint and muscle space, and the associated interpretations regarding coordinate frame coding in the CNS; 2) provides new perspectives to investigate how the CNS (and especially the low level motor networks) tunes motor commands to the ongoing posture, using the relatively well-understood circuitry of wrist system; and 3) illustrates opportunities to investigate the reference frames in which sensorimotor adaptations are coded.

ACKNOWLEDGMENTS

We thank David Lloyd for the figure of the apparatus.

GRANTS

The work was funded by the Australian Research Council.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: A.d.R. and T.J.C. conception and design of research; A.d.R. and T.J.C. performed experiments; A.d.R. analyzed data; A.d.R., R.D., and T.J.C. interpreted results of experiments; A.d.R. prepared figures; A.d.R. drafted manuscript; A.d.R., R.D., and T.J.C. edited and revised manuscript; A.d.R., R.D., and T.J.C. approved final version of manuscript.

REFERENCES


