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Interplay of Biomechanical Constraints and Kinematic Strategies in Selecting Arm Postures

Rebecca A. States
Division of Physical Therapy
Long Island University

Charles E. Wright
Department of Cognitive Sciences
University of California, Irvine

ABSTRACT. In this study, the authors examined the interplay between biomechanics and control strategies in the resolution of excess degrees of freedom at the joint level. Seven participants made aimed arm movements from 30 starting points and several starting postures to targets. Final arm postures for movements to a target exhibited substantial joint angle variation. Through regression modeling and by comparing observed final arm postures with biomechanically plausible postures, the authors identified 3 kinematic strategies: (a) Maintain deviations from the average angle at the starting point to the joint's final posture; (b) make torso rotations that are a fixed proportion of shoulder rotations; and (c) adopt a characteristic combination of 4 wrist-positioning approaches. The results demonstrated that kinematic strategies can account for substantial variance in final arm postures, if one takes into account 2 types of individual differences—those that arise inevitably from biomechanical constraints and those that reflect choices in movement strategy.

Key words: aimed movement, arm, biomechanical constraint, degrees of freedom, human, joint coordination, motor equivalence, movement strategy

The focus in considerable research has been the possible strategies that individuals use to select a given pattern of joint motion from among available patterns (Cruse, Brüwer, & Dean, 1993; Gielen, van Bolhuis, & Theeuwen, 1995; Rosenbaum, Meulenbroek, & Vaughan, 1996; Soechting, Buneo, Herrmann, & Flanders, 1995). No simple answers have emerged, even in studies restricted to the relatively simple act of selecting an arm posture at the end of aimed movements. One area of consensus is that kinematic factors alone are insufficient to enable one to resolve joint-level motor equivalence (Jordan, 1990; Kawato, Maeda, Uno, & Suzuki, 1990; Morasso & Sanguineti, 1995; Soechting et al., 1995). Although we concur that it is unlikely that individuals use kinematic factors to predict arm postures across all task situations, we believe the role of those factors has not yet been adequately evaluated. Specifically, we are persuaded that the role of kinematic factors should be reconsidered after accounting for (a) individual differences in control strategies and (b) biomechanical constraints related to the interplay between an individual's morphology and the layout of the workspace.

In research on reaching movements, it has been clearly shown that a single-valued mapping of arm postures to end-effector locations is untenable. In several studies, it has been reported that starting location, and by implication starting posture, affect final posture (Cruse & Brüwer, 1987; Fischer, Rosenbaum, & Vaughan, 1997; Soechting et al., 1995). Of those studies, however, only Cruse and Brüwer (1987) specifically investigated the influence of starting postures on final postures, and no one has identified straightforward kinematic rules for predicting final postures given information about starting locations or starting postures. Before ruling out the possibility that relatively simple kinematic strategies suffice to resolve joint-level motor equivalence, additional issues must be considered.

First, in studies related to the motor equivalence issue (Cruse, 1986; Cruse & Brüwer, 1987; Cruse et al., 1993; Dean & Brüwer, 1994, 1995; States & Wright, 1993, 1994; Vereijken, Emmerik, Whiting, & Newell, 1992) and in others on motor skill learning (McDonald, Emmerik, & Newell, 1989; Newell & Emmerik, 1989; Zanone & Kelso, 1992), the presence of substantial individual differences in joint coordination has been noted. Although the presence of individual differences is allowed for in some of the more complex computational models and in most of the theoretical statements, in little behavioral research have those differences been accounted for in a systematic way. Second, it is generally acknowledged that biomechanical constraints, such as those imposed by the interplay between end-effector location and the participant's morphology, are substantial. However, their nature and extent are largely undocu-

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Correspondence address: Rebecca A. States, Long Island University, Division of Physical Therapy, 1 University Plaza, HS 213, Brooklyn, NY 11201. E-mail address: Rebecca.States@LIU.edu

mented for the tasks typically studied in motor equivalence research. Soechting et al. (1995) have shown, though, that comparisons of observed joint postures with the set of possible postures might lead to useful insights.

The process of distinguishing the effects of biomechanical constraints from the effects of other influential factors, especially kinematic strategies, requires analyses that are more extensive than those that have generally been performed. In most previous research, the scope of such analyses has been limited, we believe, because insufficient data were collected for movements to any single target location. A change in target locations changes the biomechanical constraints operating at the end of the movement, and that complicates the process of separating the effects of biomechanical constraints from the effects of other factors influencing the final posture. In addition to studying a limited set of target locations, we found it useful to calculate the set of plausible arm postures at a target and to compare those postures with the arm postures observed there. Using those approaches, we investigated the validity of the claim that kinematic factors—based solely on movement antecedents—do not adequately account for the variation in final arm postures. Our account relies heavily on individual differences, both those that arise inevitably at the level of biomechanical constraints and those that appear to reflect different movement strategy choices.

Method

Participants

Participants were 7 right-handed Columbia University students (4 women and 3 men) with no known neurologic or orthopedic problems. They were paid to participate in multiple 1.5-hr sessions.

Apparatus

Task environment. End-effector movements were constrained to the horizontal plane and were produced by four rotational degrees of freedom: flexion and extension at the right wrist and elbow, horizontal abduction and adduction at the right shoulder, and rotation of the torso about the long axis of the spine. Our description of the number of available degrees of freedom is clearly an approximation. First, no attempt was made to distinguish torso rotation from clavicular rotation because both are relatively small (probably under 30°) and produce similar effects on right shoulder position. Second, participants were able to displace their torsos up to about 10 cm in both the x and y directions. The impact of those approximations, each of which allows more freedom than would be expected from the stated degrees of freedom, affected our analyses most when calculating plausible posture sets; hence, their impact is discussed in the Procedure section, *Calculation of plausible arm postures*.

We designed a handle that would restrict hand motion and maintain the forearm in a neutral position with respect to pronation and supination. Participants grasped a vertical dowel and rested the lateral edge of the right hand in a splint molded to the shape of the hand. The dowel and splint were permanently mounted on a disk 13 cm in diameter. Participants slid the handle and the elbow along the table surface when making movements. Silicon sheeting to reduce friction covered the bottom surfaces of both.

We minimized rotations about the long axes of the upper arm by locating the horizontal plane of movement 10–15 cm below the shoulder, using a table and chair that were adjustable in height. The table was L shaped so that participants could rest their right arm on it at their right side and in front of them. Motion of the clavicle was restricted through the use of a harness that strapped the shoulder blades against a rigid board.

Participants always had full view of their arm, the starting and target points, and the table. At each starting and target point, we used a 1.8-cm-diameter orange disk to designate wide targets. A pink disk, .9 cm in diameter, was overlaid on top of each orange disk, and designated narrow targets. Those disks were placed on the lower surface of the Plexiglas table so that they did not interfere with movement. Participants also viewed a projected image that schematically depicted the workspace. We used that image before each trial to provide instructions, and after each trial to provide feedback.

Digitizer. We measured three-dimensional locations of five active markers on the right arm by using a sonic digitizer (GTO CalComp Peripherals, Scottsdale, AZ; model GP8-3D) running at 20 Hz. We determined reliability by measuring a rod in two orientations (aligned with the x- or y-axes) at 7 locations distributed throughout the workspace. The average length of the rod was found to be 17.7 cm, and it had a standard deviation of 0.1 cm when measured across four repetitions of the 14 positions.

Marker placement was designed so that joint motion could be tracked through the horizontal plane. One marker was permanently affixed at the front edge of the base of the handle and served as a pointer. Two were mounted on the distal and proximal ends of a splint covering the medial portion of the forearm; their positions were adjusted so that they could track the centers of rotation for the wrist and elbow. We mounted the remaining markers on the right and left sides of the shoulder harness to track motion of the right shoulder and the torso.

The positions of the wrist and elbow markers were calibrated at the beginning of each session so that we could more nearly approximate the centers of joint rotation. We normalized the positions of all five markers across sessions to minimize differences in segment lengths and to maximize the accuracy of the estimation of joint centers within the horizontal plane. Calibration and normalization procedures are described in States (1994, 1997).

Calculation of joint angles. The x, y, and z coordinates for the tip of the pointer and for the centers of rotation of the right wrist, elbow, shoulder, and the left shoulder were tracked throughout every movement. We then converted the x and y components to joint angles by using an inverse-kinematics model adapted to each individual's morphology. The z values were used within the normalization procedure only to correct for motions out of the horizontal plane. We defined joint angles by using a standard radial coordinate system. For each joint, the origin is aligned with the proximal segment, and angular values increase with counterclockwise rotation. For torso rotations, the origin is at the midpoint between the two shoulder markers and the 0° axis runs parallel to the horizontal axis defined by the measurement system.

Determination of movement start and endpoints. We determined movement start and endpoints in real time by monitoring the tangential velocity of the marker that acted as the pointer. Two velocity thresholds (0.1 and 1.0 m/s) were employed. Movement start points were designated when tangential velocity increased above the low threshold. Movement endpoints were designated when tangential velocity decreased below the low-velocity threshold. If more than one endpoint was detected for a given movement, we used the first endpoint for which tangential velocity remained below the low-velocity threshold for at least 500 ms.

Procedure

Experimental design. The experiment involved three conditions tested in each of two sessions. For each condition, movements from 30 arm postures to a single target were tested as a block of trials. The set of 30 movements was then repeated for the same condition in two more blocks of trials, immediately following the first. Hence, in each session, 3 conditions × 3 blocks/condition × 30 trials/block were tested for a total of 270 movements. Trials were presented in a different random order for each block and for each participant. In the three conditions, different targets and starting positions were used; those are described later. A final variable, target width (wide or narrow, to be described later), was manipulated across sessions.

We designed Condition C30 (central target, 30 starting locations) to examine the effects of starting location. Participants made movements from 30 starting points distributed in a grid throughout the workspace to a single centrally located target (Point 35). The layout of starting and target points is shown in Figure 1A, along with a stick figure illustrating the initial posture of 1 participant on one trial. The distance between points within the grid was 12 cm in both the *x* and *y* directions.

In the two other conditions, only 10 of the 30 starting points were used so that several initial arm postures could be tested at each starting point. Those conditions were labeled *C10* (central target, 10 starting locations) and *P10* (peripheral target, 10 starting locations).

To generate various initial arm postures, we instructed participants to adopt one of three wrist angles (neutral, flexed, or extended) at the start of the movement. Figure 1B displays the 10 starting points used by 1 participant in Condition C10, along with stick figures that show representative postures for the three initial wrist positions at one of the starting points. After initiating the movement on each trial, participants were free to use the wrist and all other joints as they liked. As discussed earlier, a block of trials included 30 movements (10 starting points × 3 initial wrist positions), and the block was repeated two more times. The order of the movements was randomized separately for each block and participant. Conditions C10 and P10 differed only in that in the former the central target described in Condition C30 and shown in Figures 1A and 1B was used, whereas in Condi-

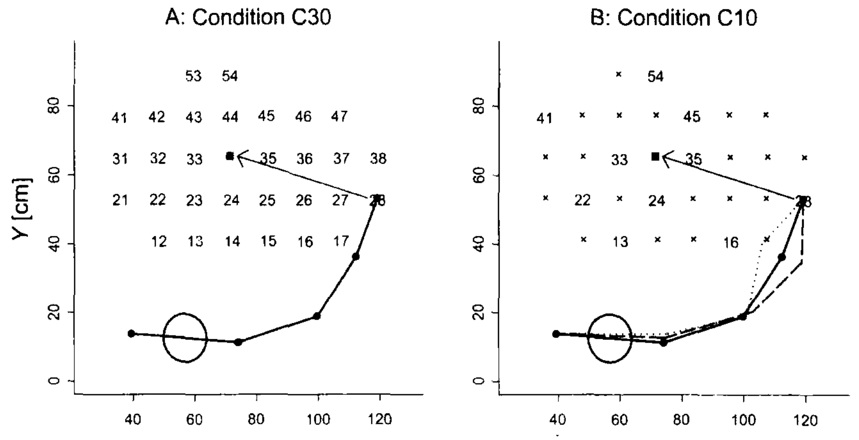

FIGURE 1. Layout of the workspace. **A**. The locations of the 30 starting points and the central target used in Condition C30 (central target, 30 starting points). The points are labeled in columns 1–8 and rows 1–5. Thus, the point in the 3rd row from the bottom and the 4th column from the left is point 34, the central target. Also included is a stick figure showing the initial posture of the arm of 1 participant for a movement from Starting Point 28 to the central target. In **B**, only the 10 starting points used in Condition C10 (central target, 10 starting points) by that participant are labeled. Also in **B** are examples of the initial postures adopted by the participant during wrist flexed (long-dashed line), neutral (solid line), and wrist extended (short-dashed line) trials from Starting Point 28. In both **A** and **B**, the arrow designates the general direction of movement, not the exact hand path.

tion P10 a peripherally located target was used. Across the group of 7 participants, three peripheral targets were examined (numbers 15, 28, and 42 as seen in Figure 1A). That procedure allowed us to test a range of peripheral targets while still having some replications across participants.

The order of the three within-session conditions, and target width, were counterbalanced across the first 6 participants. The order for the 7th participant was a replication. Before the testing reported here, participants engaged in four or five practice sessions. The first two or three practice sessions were designed so that the apparatus could be fitted to the individual and so that the participant could be familiarized with the task environment and conditions. In the last two practice sessions, the task conditions reported here were replicated, but different methods for attaching markers and for scoring movement speed and accuracy were used.

Task instructions. Participants were instructed to make fast, accurate movements. Once participants had positioned the pointer within the designated starting point, a tone sounded. The tone indicated that they were free to move to the target. Participants were under no pressure to begin their movements immediately upon hearing the tone, although they were asked to complete the movement within 6 s of the tone. After each trial, participants were shown their movement durations and a picture of the exact location of the endpoint of their movement in relation to the target. As a block of trials progressed, endpoints accumulated in the pictorial display, so participants could take note of and correct any bias. At the end of a block of trials, participants also received a score. Optimal scores were obtained by moving as quickly as possible while still hitting the target on about 90% of trials. Details of the scoring system are given in States (1994). Small cash bonuses were given at the end of the day for improved scores.

Calculation of plausible arm postures. To investigate the nature and extent of biomechanical constraints, we calculated sets of plausible arm postures. Those sets consisted of all the arm postures that were biomechanically plausible for a given participant at a given target location. From our data for each participant, we estimated segment lengths and the average location of the target relative to the midpoint of the torso. We applied those values as parameters of a forward kinematic model to generate numerous candidate arm postures. We then used the joint-angle ranges exhibited by each individual across sessions, both at the start and the end of movements, to select plausible arm postures from among the candidate postures. To be considered unique, an arm posture had to differ by at least 1° at the wrist or torso from other plausible arm postures.

An important limitation of that procedure is that it does not compensate for changes in the position of the torso relative to the end-effector across trials. Such changes occurred either because of motion of the torso relative to the workspace or because of inaccuracies in positioning the end-effector at the desired target location. To investigate how those torso displacements affected our results, we calculated sets of plausible arm postures at four extreme torso positions that were representative of the extreme values observed for each target and participant. The angle–angle plots generated from those overlapping plausible arm posture sets were not markedly different from the plausible postures associated with the average target location. Because calculating plausible posture sets for multiple torso locations resulted in irregular amounts of redundancy in the data, the data were considerably more difficult to reduce and present as simple visual summaries. Therefore, we chose to ignore those effects in our analyses and, instead, allowed observed arm posture data to fall outside the calculated set of plausible arm postures on a few trials.

Results

Performance Measures

Before focusing on the data that address our primary goals in the experiment, we summarize performance in this task. In Table 1, we provide data showing that participants responded appropriately to instructions. Movement distances varied between conditions with different targets (compare Conditions P10 and C10) and different starting points (compare the subset of starting points in C30 that do not match those in C10 and those that did) but not between conditions with different target widths, instructed wrist postures, or movement start point contexts (compare C10 start points in C30 with those in C10). Likewise, the standard deviation of the endpoint errors responded almost perfectly to the target size instructions, based on Welford's (1958) definition of expected target width (two times the standard deviation in endpoint errors). Because differences in endpoint errors between locations or between instructed wrist postures were small (16% or less), data from the two target-width conditions were pooled, resulting in approximately 180 observations for each condition. Finally, Section C of Table 1 shows that, as expected from the instructed differences in movement distance and target width, there were large differences in movement duration across conditions and target sizes.

Variation Within Final Arm Postures

We now consider postural variation within the sets of postures observed at the endpoint of the movement (final arm postures) by (a) describing the extent of variability at each joint, and patterns of interjoint correlations, across the three conditions; (b) investigating the effects of several kinematic factors related to movement antecedents such as starting posture and starting location of the end-effector; and (c) demonstrating strong individual differences in approaches to positioning the wrist.

Variability at Each Joint

Despite the fact that participants were required to finish their movements within small targets (radius of 0.9 or 0.5 cm in the wide and narrow conditions, respectively), substantial variation in final arm postures was observed. In Figure 2, the within-participant standard deviations, aver-

TABLE 1
Summary Performance Data Broken Down by Position of the Target, Number of Starting Points, Instructed Starting Wrist Angle, and Target Width

	C30		C10			P10		
Target size	Start points not in C10, Wrist neutral	Start points in C10, Wrist neutral	Wrist neutral	Wrist flexed	Wrist extended	Wrist neutral	Wrist flexed	Wrist extended
			Movement distance (cm)					
Large	29.0	26.0	25.9	26.0	25.9	37.9	37.9	37.7
Small	29.0	26.0	26.0	26.1	25.9	37.9	37.9	37.8
			Standard deviation of endpoint errors (cm)					
Large	0.423	0.441	0.403	0.415	0.459	0.395	0.414	0.453
Small	0.250	0.270	0.245	0.240	0.285	0.231	0.223	0.296
			Movement duration (ms)					
Large	506	473	480	486	523	568	562	591
Small	603	583	607	652	641	728	705	741

Note. C = central and P = peripheral targets; 10 and 30 represent number of starting points. For each participant, the 10 starting points in the C10 and P10 conditions matched 10 of the 30 starting points in the C30 condition. Each cell represents an average of the three repetitions for each of 7 participants, collapsed across participants.

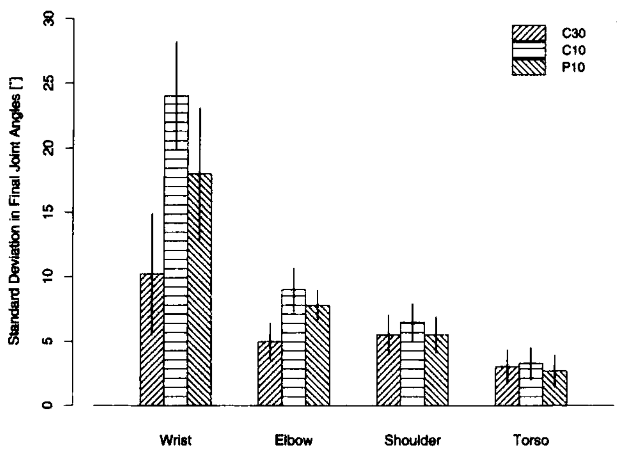

FIGURE 2. Standard deviations in final joint angles. Average within-participant standard deviations for the four different joints and three conditions. Within-participant standard deviations are shown for the final angle of each joint at the target. Bar heights show averages across participants and the two testing sessions. Error bars illustrate between-participant confidence intervals after the overall participant effects were removed. C = central target condition, P = peripheral target condition, 10 and 30 represent number of starting points.

aged across participants and target widths, are presented for the different joints and conditions.

Relationships Among the Joints

Given that there was nontrivial joint-angle variation within the final arm postures, we considered several methods for understanding that variation. One method was to test for relationships among the joints by looking at correlations between all possible pairs of joints. Ample evidence was obtained of interjoint relationships within the final arm postures, several of which are noteworthy (see Table 2). First, shoulder–torso correlations were uniformly strong and negative. Forty of 42 shoulder–torso correlations were stronger than –.65, and all were significant at an alpha level of .01 (degrees of freedom ranged from 67 to 88).

Second, in Table 2 an apparent tradeoff can be seen be-

TABLE 2
Interjoint Correlations for Pairs of Final Joint Angles

Condition	Wrist–Elbow	Wrist–Shoulder	Wrist–Torso	Elbow–Shoulder	Elbow–Torso	Shoulder–Torso
	Correlations within a plausible posture set					
C30	–.345	–.330	.208	–.603	.500	–.899
C10	–.754	–.416	.226	–.228	.270	–.853
P10	–.684	–.348	.217	–.324	.056	–.750
Mean	–.621	–.365	.217	–.399	.286	–.845

Note. Individual correlations were transformed into *z* scores, they were averaged across subjects, and the resulting values were transformed back to the *r* scale. C = central, P = peripheral, 10 and 30 represent the number of starting points.

tween the strengths of wrist–elbow and shoulder–elbow correlations. That tradeoff was borne out by individual data, as is illustrated in Figure 3 in which shoulder–elbow correlations are plotted against wrist–elbow correlations; the digits refer to the various participants. Note that although the spread was larger for some participants, each participant's data fell on that tradeoff. The shading and mark sizes in Figure 3 differentiate the data belonging to each of the three conditions, as shown in the legend. The data from the C30 condition were concentrated primarily in the lower-right end of the tradeoff, with strongly negative shoulder–elbow correlations and wrist–elbow correlations close to zero or somewhat positive. In contrast, the data from the C10 condition fell more at the opposite end of that tradeoff, and the data from the P10 condition tended to lie in the middle. Across the data in this figure, $r = -.85$, $t(19) = -6.98$, $p < .001$, suggesting a strong relationship.

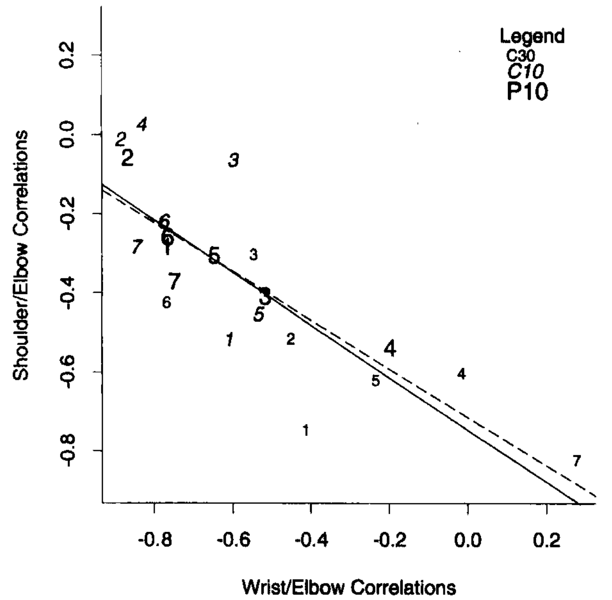

FIGURE 3. Shoulder versus elbow correlations plotted against wrist versus elbow correlations. The linear relationship between those interjoint correlations, indicated by the dotted line, suggests a tradeoff between the elbow's relationship with the wrist and shoulder. A solid line indicates the slope = 1 line, for comparison. The digits refer to the participant number, whereas the mark size and font style identify conditions as shown in the legend. Each mark represents the average correlation between the wide and the narrow target width sessions for that participant and condition. C = central target condition, P = peripheral target condition, 10 and 30 represent the number of starting points.

Effects of Kinematic Factors Related to Movement Antecedents

In the previous analyses, the nature and extent of variation in final arm postures were illustrated, whereas in this section we examine how the initial characteristics of a movement contribute to the observed variation in final postures. In particular, we examine whether either of two interdependent kinematic factors reflecting movement antecedents—starting location of the end-effector and starting posture—can account for a substantial portion of the observed variation in final arm postures.

For this purpose, we fit a number of regression models designed to predict final joint angles conditioned on a target location, given data on starting location or starting posture. For simplicity, we made separate predictions for the final angle of each joint although we considered interaction among certain of those models in our interpretation. We used combined data from both the C30 and C10 conditions so that we could explore the effects of variation in both starting location and starting posture. Those movements started from an array of 30 locations, and for 10 of those starting locations, from a range of instructed starting postures. The models were fit to the data of individual participants on the basis of data from approximately 360 movements to the central target.

Effects of Starting Location

In previous work, Soechting et al. (1995) have shown that the starting location of the end-effector influences final arm

TABLE 3
Average Across-Subjects R^2 for a Series of Models That Describe the Variation in Final Angle of Each of Four Joints as a Function of Various Indicators of Starting Posture and Starting Location

		Joint angles fit by the model			
Model used to predict final joint angle	*n*	Wrist	Elbow	Shoulder	Torso
A. StPt	28	25	25	49	46
B. lo(StDir, StDist)	20	26	23	47	45
C. StAng (all four joints)	5	61	52	64	69
D. MnStAng (all four joints)	5	16	14	39	37
E. MnStAng (all four joints) + StAngDev (one joint)	6	62	65	66	71

Note. R^2 = percentage of variance accounted for by the model. Abbreviations are defined in the text. n = degrees of freedom for each model.

posture during point-to-point movements. In that work, starting location was represented by a categorical variable as in an analysis of variance; that is, a separate parameter was fit for each level of the starting location variable. Although the fits for individual participants revealed similar effects of starting point on the final orientation angles of the forearm and upper arm, Soechting and his colleagues did not find a simple kinematic rule that could be used to explain the observed variation.

Our results confirmed the usefulness of a categorical representation of starting location as a predictor of final joint angle. For each joint of the arm, we tested regression models in which we used a categorical variable distinguishing among the 30 starting points (StPt) to predict final joint angles. For each of the four joints, the percentage of variance in final joint angles accounted for by that model is shown in Row A of Table 3. As shown, StPt accounted for between one quarter and almost one half of the total variance; the larger amount for the shoulder and torso and the smaller amount for the two distal joints. The contribution of StPt to the fit was statistically significant, $F(28, 320) > 2.0$, $p < .005$, for 27 of the 28 participant–joint combinations. The one case for which there was not a significant contribution ($p > .05$) involved the wrist.

Model A showed the maximum variance that StPt explains but did little to elucidate the relationship between StPt and final joint angles. One way one can avoid the categorical nature of the starting point predictor while still investigating the effects of starting location is to recast starting location in terms of a radial coordinate system. With Model B, we explored that possibility by substituting the predictor's starting direction (StDir) and starting distance (StDist) for the categorical predictor, StPt, in Model A. We used a radial coordinate system similar to that of Soechting and Flanders (1989). The origin moves with the body and is defined by the midpoint of the torso segment. In order to measure changes in torso angle with respect to external space, one must hold the orientation of the coordinate system constant with respect to external space. An angle of 0° was defined by a line running, roughly, through the shoulders when the participant was in a resting position, and angles increased in the counterclockwise direction when viewed from overhead.

One complication when fitting this model is that there is no a priori reason to expect a strictly linear relationship between final joint angle and StDist or, especially, StDir. Rather than force those relationships into a, possibly inappropriate, linear framework, we used generalized additive modeling[1] (Hastie & Tibshirani, 1990) for those fits. We found that by simultaneously smoothing the two variables lo(StDir, StDist), Model B accounted for a similar proportion of variance as did Model A, with fewer degrees of freedom. As desired, Model B summarized the relationship between starting point and final joint angles as a two-dimensional surface of StDist and StDir. A substantial problem of interpretation remained, however, because the shape of the predictive surface varied considerably from one participant to the next.

Effects of Starting Posture

Given those problems, we examined whether by elaborating starting position in terms of starting posture—that is, using the starting angle for each of the four joints (StAng × 4) as predictors in a linear model—we could produce a more useful model. The percentages of variance accounted for by this model are shown in row C of Table 3. Model C accounted for between one-half and two-thirds of the total variance at all four joints. Hence, Model C accounted for considerably more variance than the starting location model (Model B) but used many fewer degrees of freedom.

To better understand the predictive abilities of Model C, we explored two restricted variants. First, we asked whether the StAng predictors were useful primarily because they captured some nominal starting arm posture that related to the biomechanical constraints of the given starting location or whether the actual set of joint angles prior to the movement, as in Model C, were necessary. To explore the first possibility, we defined mean starting angle (MnStAng) for each joint as the average angle across trials at a given starting location and for a given condition (i.e., C30, C10, and P10). In our model, we used MnStAng at all four joints to predict final joint angle. Results, reported in line D of Table 3, clearly show that the MnStAng model did substantially worse than Model C at all four joints.

Second, we considered the possibility that Model D failed because it did not account for trial-to-trial variation in the predicted joint that might be retained from the beginning to the end of the movement. To examine that possibility, we added to Model D a predictor that measured the deviation between the starting angle of the joint whose final angle was being predicted and that joint's average angle for that starting point (StAngDev). Across joints, Model E accounted for the same or more variance than Model C, and significantly more than Model D for all participant–joint combinations, $F(1, 312) > 64$, $p < .001$. The success of Model E suggested that StAng can be effectively broken down into nominal starting posture plus the deviation of the joint in question from its nominal posture. Moreover, although one more degree of freedom is used in Model E than is used in Model C, four of its five predictors (MnStAng × 4 joints) actually contained less information than the four predictors in Model C (StAng × 4 joints).

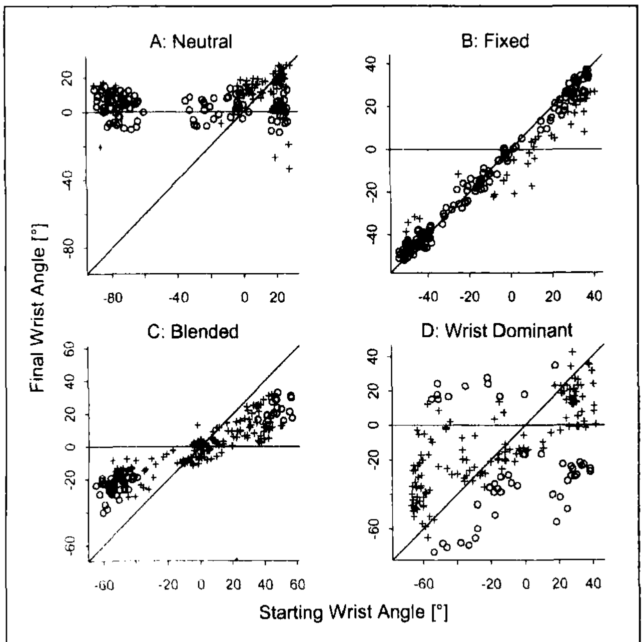

FIGURE 4. Wrist-positioning approaches. In these figures are shown examples of starting and final wrist-angle data from individual trials. They illustrate each of four wrist-positioning approaches, identified by the label on each panel and described in the text. In each panel, circles represent trials clearly adhering to the named approach, whereas crosses represent trials that were ambiguous or did not fit the approach definition. The slope = 0 and the slope = 1 lines, both with 0 intercepts, are included, because they played an important role in the category definitions. The data in each panel represent all the trials for 1 participant in one condition at one target width.

Individual Approaches to Positioning the Wrist

Having shown that kinematic strategies can account for a substantial portion of the variance in final arm postures, we also sought to investigate individual differences related to kinematic strategies. We focused these investigations on wrist movement for several reasons. First, our procedural decision to manipulate initial wrist position in Conditions C10 and P10 provided a means to examine directly how variation in wrist position at the beginning of the movement influences final wrist angle. Second, within the plausible posture sets that are described in the Procedure section (*Calculation of plausible arm postures*), the wrist joint shows the most variability. Third, in some previous studies (Dean & Brüwer, 1995), individual differences have been noted in use of the wrist during fast pointing movements.

Four Approaches to Positioning the Wrist

Data relating starting and final wrist angles did indeed suggest individual differences. We identified four approaches that are illustrated in Figure 4. Each plot shows starting and final wrist angles for all trials of a given participant in one target condition, although different participants and conditions are represented in each panel. Each trial was classified into one of the four approaches according to a set of heuristics described later. Trials that corresponded to the approach exemplified by that plot are shown as circles, all other trials as crosses. The lines in each plot have intercepts of zero, and slopes equal to zero and one.

Figure 4A shows an example in which the participant most often moved the wrist to a neutral final angle. Over 60% of the trials in that example were categorized as representing a *neutral* approach because they fell within a tolerance band of 15° surrounding the slope = 0 line.

Figure 4B illustrates a markedly different approach. Using the *fixed* approach, that participant appeared to freeze the wrist so that starting and final wrist angles were equal. Trials were classified as fixed if they fell within the tolerance band of the line with slope equal to one and intercept equal to zero, as did 80% of the trials for that participant and condition.

Figure 4C illustrates an approach we call *blended*. Here, participants moved the wrist to an angle midway between those expected for the neutral and fixed approaches. Note that the blended approach was not a simple mixture in which the wrist was frozen on some trials and moved to a neutral position in others. Trials were classified as blended if their final angles fell between the slope = 0 and slope = 1 lines but outside of the tolerance bands for the neutral and fixed approaches. Using a tolerance band of ±10°, over 60% of the trials fell in the blended category for this example.

Given the heuristics stated so far, trials whose starting and final angles were both near zero could be classified equally well as neutral, fixed, or blended. To resolve that ambiguity, we employed two additional heuristics.^{2}

In Figure 4D, a fourth approach is depicted; that approach never predominated over the other three but was evident in numerous participant–condition pairs. In those trials, wrist motion was very large (usually at least 50°); participants began with the wrist in one extreme angle and moved it beyond neutral to a new extreme angle. Although we did not verify that the wrist displacements exceeded those at other joints in all cases, that pattern held for the examples we did examine. Hence, we labeled that approach *wrist dominant*. Trials were classified as wrist dominant if they fell outside the tolerance bands for the neutral and fixed approaches and did not lie in the blended region. The wrist-dominant approach best describes over 20% of the trials illustrated in Figure 4D.

The first three approaches identified can be directly related to the StAngDev predictor. If applied universally, the neutral approach would have yielded no relationship between StAngDev and final wrist angle. In contrast, the fixed approach led to a strong correlation between StAngDev and final wrist angle, with a slope = 1. Finally, the blended approach would also have yielded a strong correlation, but with slope near one-half. The wrist-dominant approach did not yield a clearly identifiable pattern of results for StAngDev. The advantage of identifying the wrist-positioning approaches heuristically is that it allowed us to better measure how individuals combine those distinct coordinative solutions across conditions.

Use of Wrist-Positioning Approaches Across Participants and Conditions

In Figure 5, the proportion of trials falling into the four wrist-positioning approaches for each participant and condition are plotted. Several observations are noteworthy. Across participants and conditions, the fixed wrist approach was most prevalent. It best describes the majority of trials in 17 of 21 participant–condition pairs, 54% of the movements overall, and at least 15% of trials in any given participant–condition pair. Another approach widely adopted by our participants was the neutral approach. It accounted for at least a small proportion of trials made by all participants in all conditions, and at least 50% of trials in 3 participant–condition pairs. Arguably the least common of the approaches observed here was the wrist dominant, although even it accounted for at least 15% of trials in 3 participant–condition pairs.

Along with tendencies across participants, a systematic pattern across conditions is also shown in Figure 5. The fixed approach was most prevalent for the C30 condition and was least prevalent in the P10 condition, whereas the neutral and blended approaches showed the opposite pattern.

Also evident in Figure 5 are some substantial individual differences. For example, unlike all other participants, Participant 7 adopted the fixed approach for a very large percentage of trials in every condition and rarely used wrist angles classified according to any other approach. Participant 5, by contrast, made use of the neutral approach on a substantial percentage of trials in all conditions. In addition, in each condition Participant 3 made more use of the wrist-dominant approach than any other participant.

Biomechanically Plausible Arm Postures

We now focus on clarifying the relationships between the identified kinematic regularities by, among other things, considering how constraints on one joint affected the other joints. Our purpose is to distinguish between those aspects of the observed kinematic regularities that reflect strategic decisions by the motor planning system, and those aspects

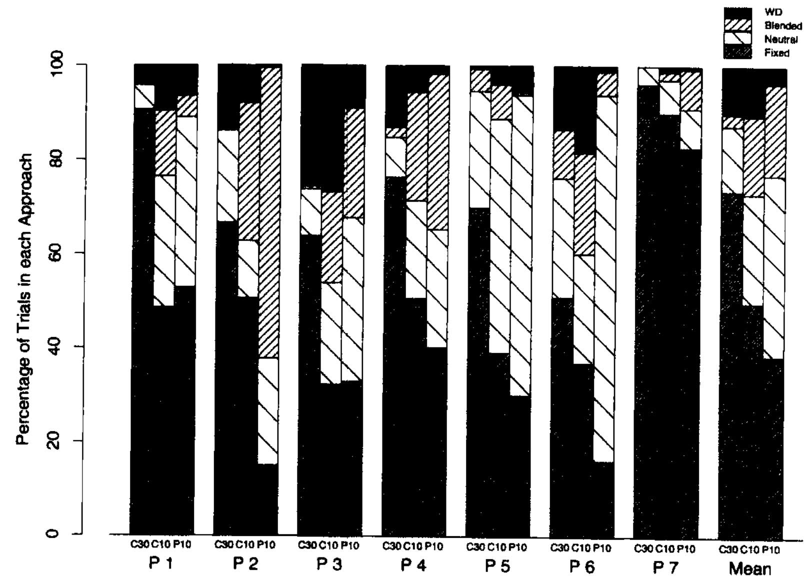

FIGURE 5. Classification of wrist-positioning approaches. The percentages of trials classified according to each wrist-approach category, as indicated by the legend, are shown for Participants 1–7 and three conditions, averaged across target widths. WD = wrist dominant. See Figure 2 for an explanation of other abbreviations.

that are better attributed to the effects of biomechanical constraints that inexorably, but not always obviously, limit posture choices to a plausible posture set. In our view, only factors that limit arm postures more strictly than the plausible posture set should be thought of as strategic.

Understanding how the biomechanics of a four-joint arm interact to constrain possible postures within a plausible posture set is not a trivial matter. To investigate that question, we juxtaposed the observed final arm postures for a given target location with the set of plausible arm postures for that location. Hence, for each participant and target location, we calculated a set of plausible arm postures as outlined in the Method section. Figures 6, 7, and 8 display the sets of plausible arm postures for Participant 2 in Conditions C10 and C30 and Participant 7 in Condition C30, respectively. We display those sets of postures as angle–angle diagrams in order to illustrate how the selection of an angular position for one joint constrains the selection of the angular position of other joints. Also included are the observed data for that participant and condition.

Torso–Shoulder Angles

The panel showing the shoulder–torso plots in these figures illustrates a consistent feature of the sets of plausible arm postures. For every participant and condition, the set of plausible shoulder and torso angles formed a narrow band. Because the observed data had to fall within that band, any sizable variation in shoulder or torso angles necessarily had to result in a strong negative correlation such as those reported in the first section of Table 2. One implication from the sets of plausible arm postures is that, even for data conditioned on a given target location, strong shoulder–torso correlations should not be interpreted as a manifestation of a strategic coupling between the shoulder and torso; instead, they were largely determined by biomechanical constraints.

Despite the strong biomechanical constraints, participants could still exhibit strategic variation in the selection of shoulder or torso angle, or both, as is shown, for example, in Figure 6. The torso angles used by Participant 2 when moving to the central target ranged from about –5° to about +5°, which is about one-third of the possible range. Even within that limited range of torso angles, the observed postures tended to be those with more positive shoulder angles. Those limitations in the use of shoulder and torso postures were consistent across participants and targets, as can be seen, in part, by examining Figures 7 and 8.

Wrist–Elbow and Elbow–Shoulder Correlations

A more complex interjoint relationship observed in our data was introduced in Figure 3. That figure shows a tradeoff between wrist–elbow correlations and elbow–shoulder correlations across participants and targets. Understanding

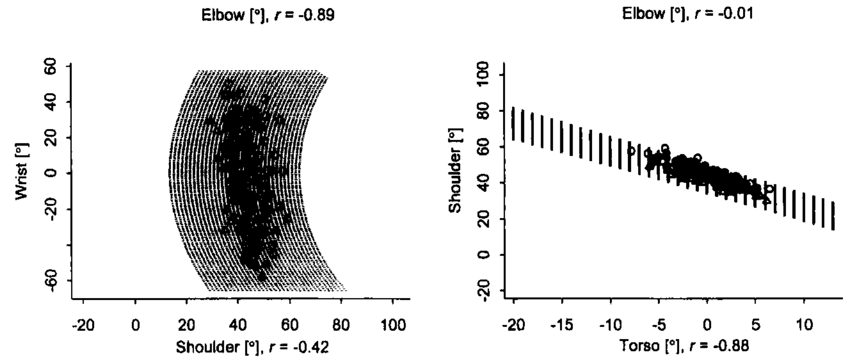

FIGURE 6. Plausible and observed arm postures at the central target for Participant 2 in Condition C10 (central target, 10 starting points). The four angle–angle plots illustrate the set of plausible arm postures (shown as dots) available to that participant at the central target. Also included are the observed arm postures, shown as circles for the wide target-width session and as triangles for the narrow target-width session. The plausible arm postures appear to fall along contour lines, which resulted from our procedure for identifying unique postures. The postures on a line in any of the panels are those that share a given torso angle; each contour line represents a 1° change in torso angle. The successive points along a line are postures with wrist angles differing by 2°. The *r* value under each panel is the correlation between the observed angles of the two joints shown in that panel.

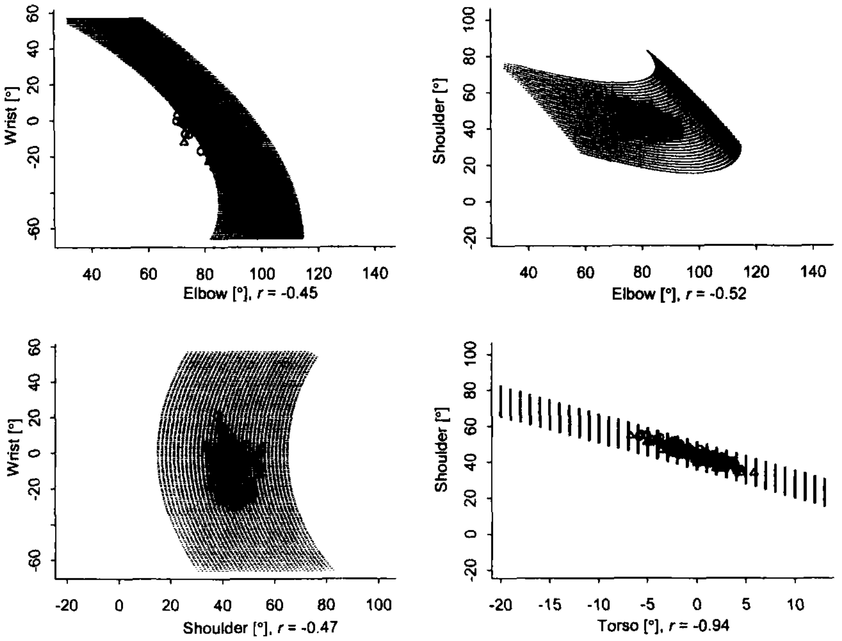

FIGURE 7. Plausible and observed arm postures at the central target for Participant 2, Condition C30 (central target, 30 starting points). The format of these panels is the same as in Figure 6.

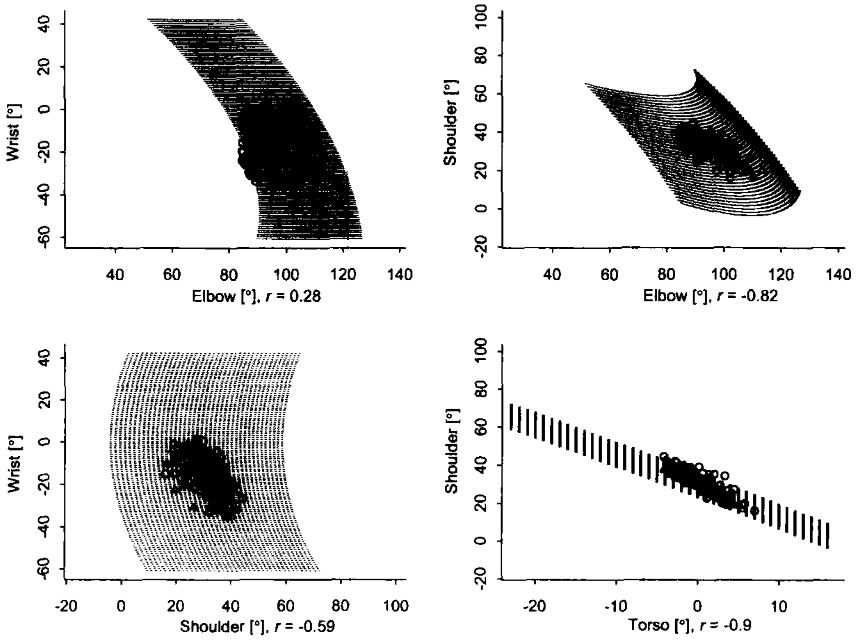

FIGURE 8. Plausible and observed arm postures at the central target for Participant 7, Condition C30 (central target, 30 starting points). The format of these panels is the same as in Figure 6.

that tradeoff requires explanations of (a) the constraints on those correlations that led to the, approximately linear, observed tradeoff and (b) the causes of the variation along that tradeoff across targets and participants.

We illustrate our explanations for both issues by using the sets of plausible arm postures in Figures 6–8. In short, we argue that (a) biomechanical constraints, reflected in the isotorso-angle contours of the wrist–elbow and shoulder–elbow panels of those figures, limited those correlations to the observed tradeoff. In addition, (b) the location of a set of data within that tradeoff was the result of the relative magnitudes of two sources of variation—that within the biomechanically coupled shoulder–torso pair and that dictated by the participant's approach for positioning the wrist.

To see how the wrist-positioning approaches and the biomechanical constraints interacted to modify those interjoint correlations, look first at the wrist–elbow panel in Figure 7. For that participant in that condition, there was little wrist-angle variation; the distribution of the observed final wrist angles included only about one third of the range produced by that participant throughout the course of the experiment. The variation in final wrist angles was relatively small because Participant 2 used a fixed-wrist approach and, in that condition (C30), there was no instructed wrist-angle variation at the starting point.

Next, take note of the contour lines within each panel of Figure 7 (for a definition of the contour lines, see the caption for Figure 6). As was true for all participants and conditions, the isotorso-angle contours in the wrist–elbow panel run steeply from the upper left to the lower right, but those contours are almost horizontal throughout most of the elbow–shoulder panel. Given the consistent range of shoulder and torso angles noted earlier, the horizontal spread of the wrist–elbow data points across various isotorso-angle contours may have simply reflected spread in the shoulder–torso angles. The spreading across isotorso angle contours in combination with the lack of wrist-angle variation may have produced the observed wrist–elbow correlation, which, in Figure 7, is of middling size ($r = -.45$). Referring back to Figure 3, we would expect this moderate wrist–elbow correlation to be paired with a similarly moderate elbow–shoulder correlation, which, in fact, it was ($r = -.52$). Note that the elbow–shoulder correlation may have been a simple reflection of the variation in torso and wrist angles that has already been discussed.

For comparison, look now at Figure 6, which shows data for the same participant moving to the same target. The crucial difference is that Figure 6 refers to Condition C10 in which the participant was required to adopt flexed and extended as well as normal wrist postures before the start of the movement. Because that participant used the fixed-wrist approach, the variation in initial wrist angle led to substantial variation in final wrist angle. That variation increased the vertical scatter of the points in the wrist–elbow panel and generated a stronger wrist–elbow correlation ($r = -.89$). Because the target position for all of those movements was the same, the increased wrist-angle variation must have been compensated for by postural changes at the other joints. Most interesting, there was almost no change in the magnitude of variation at the torso or shoulder, whereas the elbow angle variation is almost twice as large in Figure 6 as in Figure 7.

Considering the natural orientation of the joints near the center of the workspace, it is not surprising that the bulk of the compensation came from adjustments in elbow angle. Figure 3, which illustrates the tradeoff between wrist–elbow and elbow–shoulder correlations, led us to expect that a strongly negative wrist–elbow correlation would be associated with an elbow–shoulder correlation of small magnitude. The panel of elbow–shoulder data in Figure 6 confirmed that expectation. In the elbow–shoulder panel of Figure 6, one can see that the larger elbow angle variation, combined with a lack of increased variation in shoulder angles, caused an increase in the horizontal scatter of the data points. That increase in horizontal scatter reduced the strength of the elbow–shoulder relationship and resulted in no correlation ($r = -.01$).

Figure 7 is an example of data with wrist–elbow and elbow–shoulder correlations that place the figure in the middle of the tradeoff illustrated in Figure 3. Figure 6 illustrates one extreme of that tradeoff: a strongly negative wrist–elbow correlation combined with a zero elbow–shoulder correlation. In Figure 8, we illustrate the other extreme by using data from a different participant. In those data, the variation in the wrist angles was relatively small, whereas the ranges of shoulder and torso angles remained similar to those seen in Figures 6 and 7. The result was that the wrist–elbow correlation was mildly positive ($r = .28$) and the shoulder–elbow correlation was strongly negative ($r = -.82$).

We believe those data suggest that the tradeoff between wrist–elbow and elbow–shoulder correlations does not reflect a subtle shift of strategy as we once thought possible. Instead, it resulted from a combination of the wrist-positioning approaches previously described and the complex biomechanical constraints that occurred among all four joints when the end-effector was constrained to the target position.

The Influence of Starting Position on Shoulder and Torso Angles

Finally, we consider how the structure apparent in the plausible posture sets influenced our interpretation of the effects of movement antecedents. Recall that in our modeling work those influences were summarized as the effects of the average starting postures of all four joints at a given starting point, along with the effects of the deviation from that posture for the joint in question (Model E in Table 3). We focus here on the effects of average starting posture of the shoulder and torso, because (a) the effects at the wrist are best summarized in the previously described wrist-positioning approaches and (b) an examination of the coefficients for each of the average starting joint-angle predictors showed the effects of the elbow predictor to be quite small.

To illustrate how average starting joint angles influenced final shoulder and torso angles, we elaborate on the shoulder–torso plots shown in Figures 6, 7, and 8. The shoulder–torso data from Figures 6 and 7 are redisplayed in Figure 9, but include within them arrows that originate at the arm posture adopted at the start of the movement and point to the arm posture adopted at the end of the movement.

The most important observation gathered from Figure 9 is that the starting point of all the arrows, as well as the arrows themselves, lie within a diagonal band reaching from the lower left to the upper right of both plots. That finding demonstrates that regardless of starting posture, the shoulder and torso joints moved proportionately. Note, that

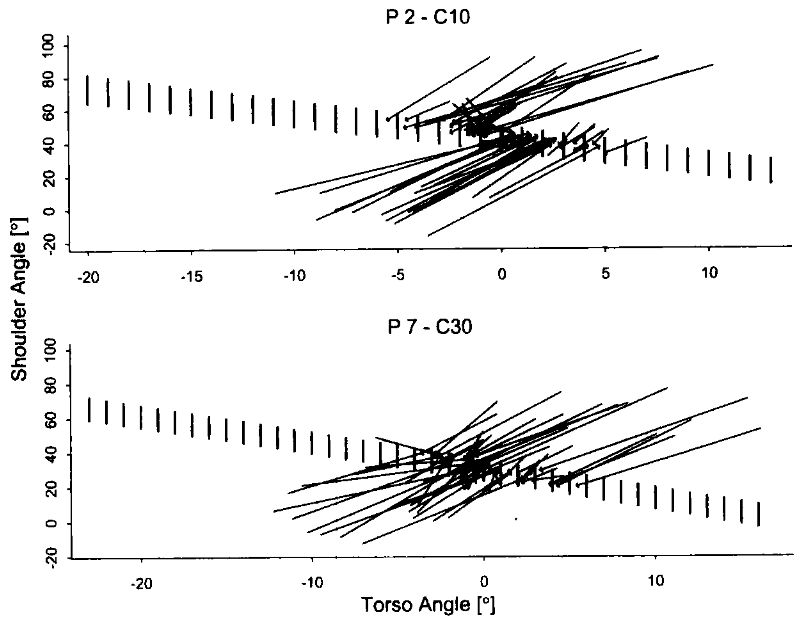

FIGURE 9. Starting-to-final-posture arrows. Starting-to-final-posture arrows indicate a shoulder and torso synergy. Plausible and observed data for the shoulder and torso for Participant 2, Condition C10 (central target, 10 starting points) and Participant 7, Condition C30 (central target, 30 starting points), as shown in Figures 6 and 8, are reproduced in the top and bottom panels, respectively. Added to those plots are arrows whose origin indicates the initial posture and whose head indicates the final posture. Each arrow represents the average across repetitions for a given starting location and initial wrist posture.

did not have to be the case. Participants could have moved from their chosen starting postures to any point within the plausible posture band; they need not have followed a similar pattern for all movements. The pattern of starting-to-final posture arrows in Figure 9 is consistent across participants and conditions, and was captured by the average starting angle models (Models C, D, and E in Table 3). In other words, in Figure 9 it is evident that the average starting angles for the shoulder and torso collectively influenced the final posture of both joints. Most interesting, they did so in a manner that was consistent across starting points but that still allowed for trial-to-trial variation.

Discussion

We designed our study to investigate the interplay between biomechanical constraints and kinematic strategies when selecting arm postures at the end of fast and accurate pointing movements. Although we did not attempt to quantify the relative importance of those two factors, in our study we have demonstrated that (a) biomechanical constraints can impose pervasive, but subtle, regularities that limit the number and array of available postures and (b) there are kinematic regularities that cannot be attributed solely to biomechanical constraints. We attribute those kinematic regularities to movement strategies, although we acknowledge that one cannot identify with our descriptive analyses how the motor system represents and implements those strategies.

In our movement task, participants appeared to resolve the joint-level ambiguity in final postures by using three strategic regularities or some recombination of their implied constraints. The first and most general strategy was the tendency to maintain deviations from the average starting joint angle associated with an end-effector location so that final angles deviated in a similar manner. That strategy was most obvious for the elbow, shoulder, and torso joints. The second strategy was to make torso rotations that were a fixed proportion of the concurrent shoulder rotations. The third strategy was to adopt a characteristic combination of the four identified wrist-positioning strategies and to maintain that basic combination across task conditions. Those three strategies together explain roughly three quarters of the variation in joint angles for movements to a target in the middle of the workspace.

Our description of that process is far from complete, however. Specifically, there are only two excess degrees of freedom within the observed biomechanical system. A clear inference is that all three of those strategic constraints cannot have their full influence simultaneously. The apparent contradiction is mitigated somewhat because the most common approach for positioning the wrist—the fixed approach—represents a special case of the first strategy: maintaining deviations from the average starting posture through to the final posture. Clearly, a complete description of the application of those strategic constraints must include a process description that explains the causal linkages among the strategies and the manner by which they are to be reconciled with the limited degrees of freedom available.

Regardless of that limitation, it is important to note that individuals can implement all three of the constraints by using a planning process that operates before the movement begins solely on the basis of kinematic information about the current arm posture and the location of the target. We do not mean to imply that those constraints could not be implemented by a dynamic process driven by kinetic considerations, for example, but rather that such a system is not necessary as an explanation of our results.

At least for us, a second important result of this exploration is the lessons that it provides about the complexity of the biomechanical constraints within this task. In particular, several relationships that we observed and, initially, thought to be the result of strategic choices made by our participants instead reflected those biomechanical constraints, or the operation of more fundamental strategic decisions translated through those biomechanical constraints. The correlation of shoulder–torso angles and the tradeoff between wrist–elbow and elbow–shoulder correlations are the two obvious examples. That lesson is particularly instructive because, having limited our observations to joint postures within a plausible posture set, we felt that we had largely eliminated such biomechanically induced artifacts.

Next, our results strongly support the position that final arm postures are not uniquely determined by end-effector location when redundant degrees of freedom are available. That finding concurs with recent studies in which the variation in final arm postures has been precisely analyzed (Gielen, Vrijenhoek, Flash, & Neggers, 1997; Soechting et al., 1995; Theeuwen, Miller, & Gielen, 1993), although it contradicts earlier studies (Hore, Watts, & Vilis, 1992; Miller, Theeuwen, & Gielen, 1992; Soechting & Flanders, 1989). Data from the early studies may have been misleading because, in the formal analyses, arm postures for many end-effector locations were considered but the biomechanical constraints imposed by the interplay between end-effector location and an individual's morphology were not adequately accounted for.

Finally, our efforts at distinguishing between models based on starting joint angles rather than on starting locations of the end-effector lend support to Rosenbaum's hypothesis about the prominence of postural information when planning arm movements. In his knowledge model (Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995), he described a formal mechanism for planning arm postures at the end of movements, and suggested that final arm postures will be influenced by starting postures even when the initial location of the end-effector remains constant. We found that mean starting joint angle, along with the deviation in starting joint angle, predicted final joint angle better than did information about the direction and distance of the starting point from the target. That finding suggests that information about initial arm postures is important in determining final arm postures. The results of empirical work related to the selection of final arm positions (i.e., the location of the end-effector at the end of a pointing movement) also suggest that postural information plays a crucial role in planning arm movements (Rosenbaum, Meulenbroek, & Vaughan, 1999; Rossetti, Meckler, & Prablanc, 1994).

In conclusion, our data showed that one can use systematic kinematic relationships to account for substantial portions of the variability seen in arm postures adopted at the endpoints of fast and accurate pointing movements in the horizontal plane. Some of those effects can be attributed to biomechanical constraints because they represent fundamental characteristics of the biomechanically plausible posture sets. Other kinematic regularities may be considered strategic because they are not obligatory features of the plausible posture sets and, in some cases, they differ across individuals and task conditions.

Understanding the interplay among factors such as (a) the complex interrelationship across several joints, (b) individual differences in morphology and the mapping of locations in space onto the biomechanical workspace, and (c) individual differences in movement strategies clearly requires further investigation. In our task, it may be interesting to speculate whether the observed differences in wrist-positioning approaches, in conjunction with the biomechanical constraints, might have led to widespread consequences, such as the varying tradeoff between wrist–elbow and elbow–shoulder correlations. In any case, the present analyses, together with analyses of postures sampled across target locations, highlight the complexities inherent in linkage systems with even just two excess degrees of freedom. As such, they emphasize the need for continued development of analytic and theoretic tools for interpreting movements with excess degrees of freedom, perhaps with the immediate goal of generating a more precise and succinct vocabulary for multijoint coordination.

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NOTES

1. Generalized additive models are an extension of generalized linear models. In both, one uses local smoothing functions (in this case, loess fits) to let the data determine the form of a smooth function. In the generalized linear model the dependent variable is smoothed on the basis of one of the predictors, whereas in the generalized additive model the dependent variable is smoothed on the basis of multiple predictors. In both cases, one can control the level of smoothing and stiffness of a loess fit by specifying the span of the

smooth, that is, the amount of data on either side of the point being approximated that are included in the weighted, local average.

2. First, points within 5° of both lines were considered ambiguous and were attributed to whichever of the three approaches predominated for that condition. Thus, in Panel A, points within 5° of both the slope = 0 and the slope = 1 lines were attributed to the neutral approach; whereas in Panel B, similar points were attributed to the fixed approach; and in Panel C, such points were attributed to the blended approach. (The attribution of those ambiguous movements did not, however, markedly alter the breakdown of movement by approach; simply omitting the ambiguous cases would not appreciably alter the results.) Second, all points that fell outside of that ambiguity zone but within the tolerance limits of at least one line were classified according to the line they were closest to. For example, in Panel A, a number of points are seemingly near the intersection of the two lines but were not classified as fitting the neutral approach. We did not so classify them because they fell outside of the 5° ambiguity zone and were closer to the slope = 1 line than to the slope = 0 line. Points that fell outside the ambiguity zone but within the tolerance band of the line characterizing the nondominant approach can also be seen in Panels B and C surrounding the intersection of the two lines. The ambiguity zone was always set to 5°, whereas the size of the tolerance band was determined through visual inspection for each participant. It was set at ±15° for Participants 1, 3, 4, 5, 6, and 7. Participant 2 was assigned a tolerance band of ±10° because her data were tightly clustered and, in one case, were about a line whose slope was intermediate between 1 and 0. When we used the larger tolerance band, that pattern was obscured.

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