Do Arm Postures Vary With the Speed of Reaching?

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Nishikawa, Kiisa C., Sara T. Murray, and Martha Flanders. Do arm postures vary with the speed of reaching? *J. Neurophysiol.* 81: 2582–2586, 1999. For reaching movements in one plane, the hand has been observed to follow a similar path regardless of speed. Recent work on the control of more complex reaching movements raises the question of whether a similar "speed invariance" also holds for the additional degrees of freedom. Therefore we examined human arm movements involving initial and final hand locations distributed throughout the three-dimensional (3D) workspace of the arm. Despite this added complexity, arm kinematics (summarized by the spatial orientation of the "plane of the arm" and the 3D curvature of the hand path) changed very little for movements performed over a wide range of speeds. If the total force (dynamic + quasistatic) had been optimized by the control system (e.g., as in a minimization of the change in joint torques or the change in muscular forces), the optimal solution would change with speed; slow movements would reflect the minimal antigravity torques, whereas fast movements would be more strongly influenced by dynamic factors. The speed-invariant postures observed in this study are instead consistent with a hypothesized optimization of only the dynamic forces.

INTRODUCTION

Soechting and colleagues (1995) showed that the final arm posture at the end of a reach could be predicted from the initial posture by assuming that kinetic energy (a dynamic, force-related parameter) was minimized. Although the kinetic energy of fast movement is greater than the kinetic energy of slow movement, this hypothesis predicts the same final posture when comparable movements are performed at a wide range of speeds. This is because the dynamically optimal posture depends only on the geometry of the mass distribution of the arm, with arm movement following the path of least inertial resistance. However, despite the excellent fit of the experimental data to this dynamic prediction, the study of Soechting et al. (1995) was limited to movements at the subjects' preferred speed (~100 cm/s peak velocity), and whether the prediction also holds for slower speeds remained to be tested.

As illustrated schematically in Fig. 1*A*, there is a trade-off between the quasistatic and the dynamic components of the forces involved in producing reaching movements. The quasistatic (antigravity) contribution (Fig. 1*A*, shaded line) dominates at slow speeds, and the dynamic component (solid line) becomes more important at higher speeds (see also Atkeson and Hollerbach 1985; Hollerbach and Flash 1982). If slow movements were primarily governed by an optimization of antigravity torques and fast movements were dominated by an optimization of dynamic torques, then the final posture should change with speed. The final arm plane (the plane formed by the shoulder, elbow, and wrist) should approach a vertical arm plane at the slowest speeds because this is the posture that minimizes the antigravity torques at the shoulder (0-intercept in Fig. 1*B*).

The purpose of this study was to test whether the arm follows the same path and reaches the same final posture for a range of movement speeds. Although speed invariance has been reported for planar arm movements (Atkeson and Hollerbach 1985; Flanders et al. 1996; Soechting and Lacquaniti 1981), we are aware of no study of speed effects on arm postures for movements to targets in three-dimensional (3D) space. A secondary purpose of this study (as discussed subsequently) was to attempt to repeat the demonstration of a dramatic dependence of final posture on initial posture for remembered (as well as visible) target locations.

METHODS

Four subjects (2 male, 2 female) participated in these experiments and gave their written consent to all experimental procedures, as approved by the University Human Subjects Committee. The purpose of the experiment was unknown to the subjects. The only instructions given were the starting location, ending location, and desired speed ("fast," F; "normal," N; or "slow", S). The first subject was instructed that fast meant to move as fast as he could, whereas (to avoid dynamic overshoots) the other subjects were instructed to move faster than normal but not quite as fast as possible. The seated subjects held a pen-shaped stylus at the initial target and moved the tip to the final target when a tone was heard. Subjects were asked to refrain from bending the wrist (holding a pen tends to reinforce this instruction). All targets were indicated by 1 × 1 cm fluorescent markers, weighted, and suspended from the ceiling. Accuracy was not emphasized, and subjects tended to stop just short of the target without hitting it.

Arm movements began or ended at one of five target locations (Table 1). These locations were chosen based on the results of Soechting et al. (1995). Of the 5 × 4 × 3 possible combinations of starting location, ending location, and movement speed, only 15 were covered during the experiments. These were Left to Center (F, N, and S), Upper Right to Center (F, N, and S), Lower Right to Upper Left (F, N, and S), Upper Left to Lower Right (F, N, and S), Upper Right to Left (F), Lower Right to Center (N), and Upper Left to Center (N). We analyzed each of the conditions where the target combination was covered at all three speeds (the first 4 target combinations listed previously). The extra movements were included in the experimental design to prevent subjects from memorizing target locations in the first ("virtual target") part of the experiment. Subject 1 performed five repetitions of each movement type, whereas the other subjects performed seven repetitions. All trials were presented in random order.

For each subject, the experiment consisted of two parts. First, the subject reached for a "virtual" final target, which was removed from view <1 s before the tone. In the second part, the subject reached for

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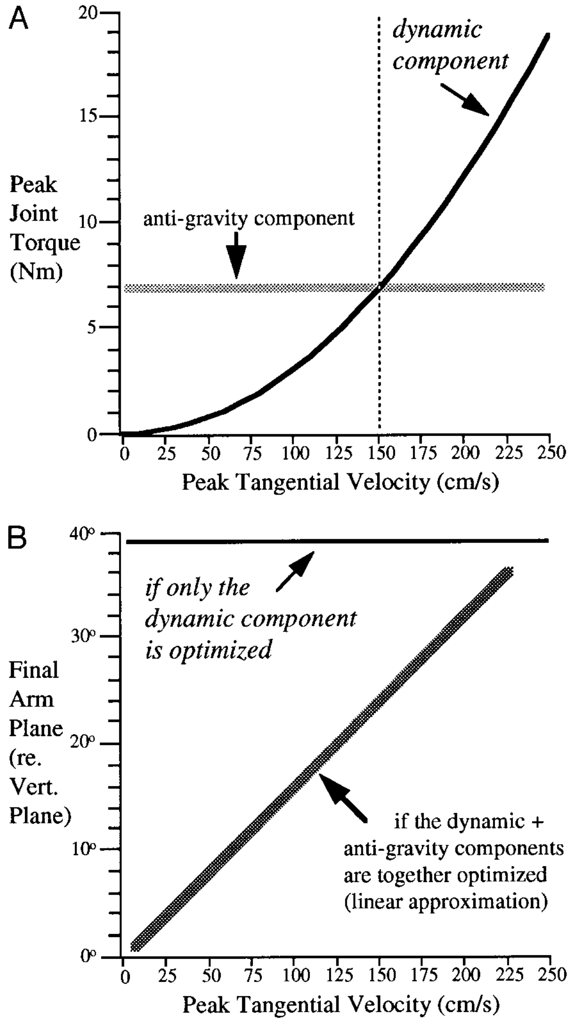

FIG. 1. The trade-off in the relative importance of anti-gravity torques (*A*, light shaded line) and dynamic torques (*A*, solid line) should lead to a variation in arm kinematics with movement speed (*B*, medium shaded line) if the total torque is the object of an optimization algorithm. Although this effect should be nonlinear, with the sign convention and targets employed in this study (0 corresponding to a vertical plane and +90° corresponding to the horizontal plane), the linear estimate should have positive slope. For most targets it should also have a zero intercept because holding the arm in the vertical plane minimizes shoulder torques. In contrast, the prediction for a dynamic-only optimization has a constant value (*B*, solid line), and for the targets used by Soechting et al. (1995) it was always positive (ranging from approximately +10° to +50°). In *A*, typical values for peak joint torque were taken from shoulder–elbow movements in a vertical plane, in the study of Soechting and Lacquaniti (1981). Proof of the form of the scaling is given by Hollerbach and Flash (1982).

a "real" target, which was present during the entire movement. For each part, we analyzed a sample [$n = 4 \times 3 \times$ (5 or 7 repeats)] of four target combinations at three speeds. Thus we analyzed a total of 60–84 trials per subject for each part of the experiment.

Arm movements were videotaped at 60 fields/s with two video cameras (VP110, MotionAnalysis). Spherical reflective markers were placed on the right arm of each subject at the shoulder, elbow, wrist, and also at the tip of the pen. The location of the markers in 3D space was computed in each field during the arm movements. Arm posture was calculated from the *x*-, *y*-, and *z*-coordinates of the shoulder, elbow, and wrist markers; hand path curvature was taken from the pen marker. The time of movement end was judged from the tangential velocity of the pen.

The most economical (in terms of number of variables) way to define arm posture for a given hand location is the parameter υ, which specifies the angle that the normal (**p**) to the plane of the arm makes with the horizontal plane (Soechting et al. 1995). Once υ is determined, the shoulder angles (η = yaw angle, θ = upper arm elevation, and ζ = angle of humeral rotation) are uniquely determined, and the elbow angle (ϕ) depends only on the distance of the target (or hand) from the shoulder. Path curvature was quantified with a standard index representing the maximum perpendicular distance of pen tip from a straight line from path beginning to end divided by the length of this straight line (Atkeson and Hollerbach 1985). Index of curvature typically has a counterclockwise–clockwise sign convention with values of ±0.5 representing semicircles. However, because in this study paths were in 3D and speed effects were very small, we used unsigned values multiplied by 100% (thus a semicircle would have 50% curvature).

The final posture of the arm and curvature of the hand path were regressed against "speed" separately for each target combination and each subject. Speed was measured as the peak tangential velocity of the pen and ranged on a continuum from ~20 to 300 cm/s, despite instructions to move at only three speeds. As illustrated schematically in Fig. 1*B*, significant positive regression coefficients for the plots of arm posture versus peak velocity would be taken as evidence for an effect of speed.

RESULTS

In both the real- and virtual-target conditions, all subjects showed a pattern of final arm planes that consistently differed according to the initial arm posture. Figure 2 illustrates these results for subject 1. When the subject reached from the Upper Right target (Up/R) to the real Center target (Ctr), final arm planes ranged from 35 to 47°. Likewise, for these same target locations but with virtual targets, the final arm planes ranged from 36 to 51°. However, when the subject reached from the Left target (L) to the Ctr target, final arm planes ranged from 12 to 20° for the real targets and from 9 to 24° for virtual targets. Thus final arm plane was dependent on the initial posture of the arm. The pattern of variation was very similar to that seen previously for real targets (Soechting et al. 1995) and now can be seen for virtual targets as well.

In contrast to the large and consistent influence of initial position, there was relatively little influence of movement speed on the progression of the orientation of the arm plane (Fig. 2). In this figure, movement times have been normalized, and the peak velocity of each trial is represented by color, with the red line being the fastest, yellow to blue representing intermediate speeds, and gray, brown, and black being the slowest. Although one can observe some dynamic overshoot for the fastest movements (*red traces*), in most cases movements of different speeds follow a similar series of postures.

In moving from the L target to the virtual Ctr target (Fig. 2, *bottom right panel*), the variation in final arm planes across fast

TABLE 1. *Approximate locations of targets relative to the shoulder*

Targets	Distance, cm	Azimuth, °	Elevation, °
Left (L)	+54	−45	+1
Center (Ctr)	+47	−8	+1
Upper Left (Up/L)	+74	−25	+24
Upper Right (Up/R)	+51	+16	+28
Lower Right (Dwn/R)	+44	+27	−37

Positive directions are to the right of a parasagittal plane for azimuth and upward from a transverse plane for elevation.

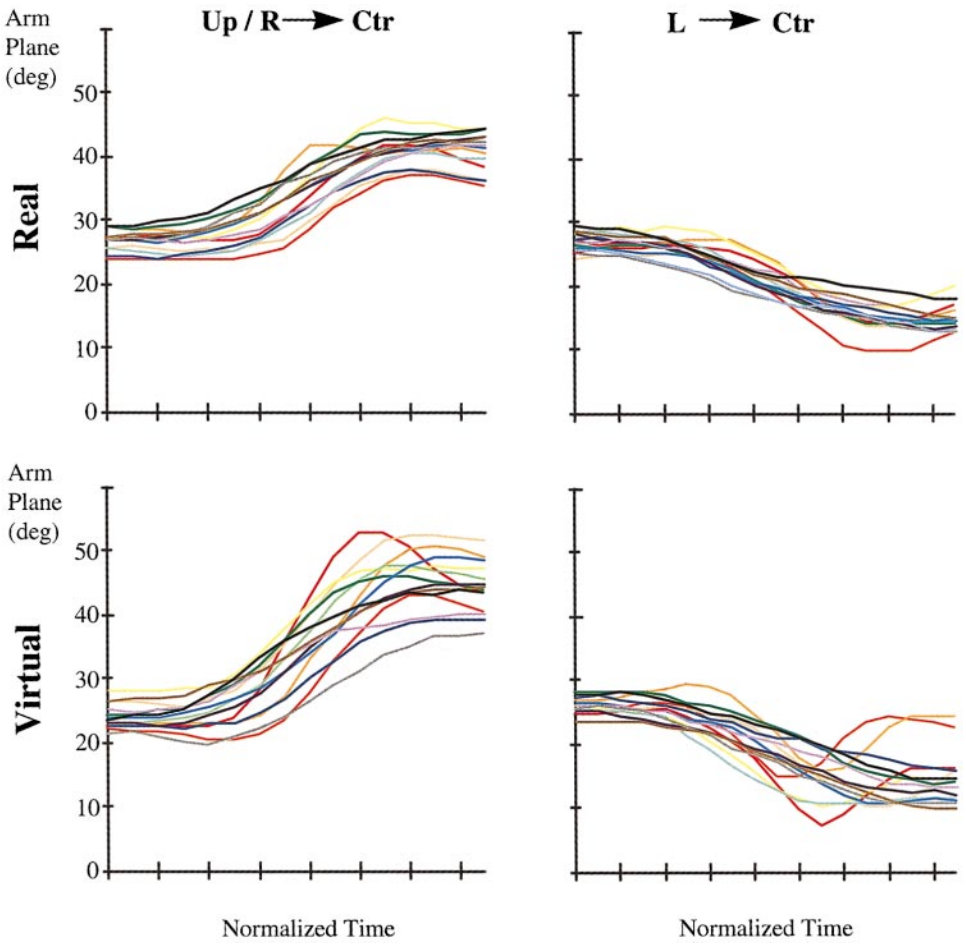

FIG. 2. Inclination of the plane of the arm (arm plane) plotted as a function of time for subject 1. Arm plane is defined as the angle between the horizontal plane and the perpendicular to the plane formed by the shoulder, elbow, and wrist. Movement was from the Upper Right target (Up/R) to the Center target (Ctr) for the graphs on the left, and movement was from the Left target (L) to the Center target (Ctr) for the graphs on the right. *Top graphs*: trials with real targets; *bottom graphs*: trials with virtual targets. *Colored lines*: different movement speeds. In each panel, the red line represents the fastest movement, and the black line represents the slowest movement, with orange, yellow, green, blue, violet, gray, and brown representing intermediate speeds. (For example, in the *bottom left panel*, red ≈ 290 cm/s, yellow ≈ 170 cm/s, blue ≈ 90 cm/s, and black ≈ 50 cm/s.) The timescale was normalized to facilitate comparison among trials with different speeds. Although all movements were to the same target, final arm plane differed depending on the starting position.

and slow movements was statistically significant ($P < 0.01$) for subject 1. This result is tabulated in Table 2, which also summarizes the relation between final arm plane and peak velocity for all four subjects and all eight conditions [nonsignificant ($P > 0.05$) regression coefficients are in parentheses, highly significant ($P < 0.01$) coefficients are in boldface type]. Subject 1 also showed significant speed effects for the Lower Right (Dwn/R) to the real Upper Left target (Up/l, $P < 0.01$) and for the Up/R to the real Ctr target and the Dwn/R to the virtual Up/l target (both $P < 0.05$). These significant slopes, however, were quite shallow and were both negative and positive, ranging from −0.04 to +0.03°/cm/s. Negative slopes run opposite to the predictions for total force (dynamic + antigravity) optimization (Fig. 1*B*). In the four other movement conditions listed here, slopes for subject 1 ranged from 0.00 to ± 0.01°/cm/s and were not significantly related to peak velocity ($P > 0.05$).

TABLE 2. *Slopes of the relation between final plane of the arm and peak velocity of the movement*

	Subject 1	Subject 2	Subject 3	Subject 4
Up/R → real Ctr	−0.03	(+0.01)	(+0.02)	(−0.01)
Up/R → virtual Ctr	(+0.01)	**+0.05**	(+0.03)	(+0.04)
L → real Ctr	(+0.01)	+0.02	(+0.03)	−0.03
L → virtual Ctr	**+0.03**	−0.02	(−0.04)	(−0.02)
Dwn/R → real Up/L	**−0.04**	(+0.00)	(+0.03)	(−0.00)
Dwn/R → virtual Up/L	−0.02	(+0.01)	(+0.02)	(+0.00)
Up/L → real Dwn/R	(−0.00)	**−0.02**	(−0.00)	−0.05
Up/L → virtual Dwn/R	(−0.00)	(+0.00)	(+0.01)	(−0.01)

Values are in °/cm/s. Entries in boldface are significant at $P < 0.01$; those in parentheses are not significant; others are significant at $P < 0.05$.

Figure 3 shows plots of final arm plane versus peak velocity for all subjects for movements involving Up/R, Ctr, and L targets. Again one can see that the final posture at the Ctr target differed depending on the initial target. For the movement from the Up/R to the real Ctr target (Fig. 3, *top left panel*), only subject 1 (■) showed a significant speed effect, but it was negative instead of positive ($P < 0.05$, see Table 2). For the movement from the Up/R target to the virtual Ctr target (Fig. 3, *bottom left panel*), all subjects showed a positive correlation, but only subject 2 (□) showed a significant speed effect ($P < 0.01$, see Table 2). As summarized in Table 2, for a given movement condition, typically one or two subjects showed a significant speed effect, but significant slopes were shallow and often differed in sign. In the most extreme cases (subject 2: +0.05; subject 4: −0.05), a threefold speed increase (from 50 to 150 cm/s) was accompanied by a variation of 5° (0.05°/cm/s × 100 cm/s) in the spatial orientation of the arm plane, but both negative and positive values were observed. The average variation (across subjects and conditions) for a threefold speed increase was +0.09°. This is well within measurement error and is negligible compared with the 20–30° variation with initial posture.

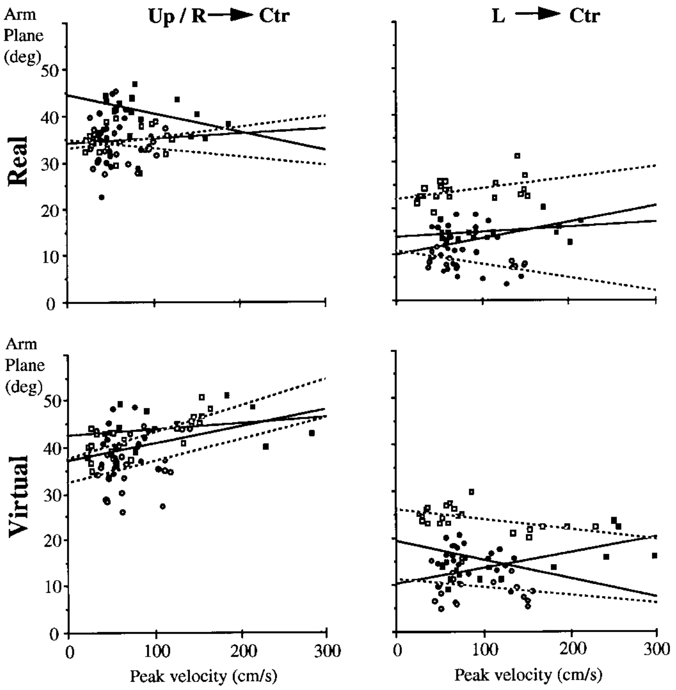

FIG. 3. Inclination of the final arm plane plotted as a function of peak velocity for all subjects. Movement was from the Upper Right target (Up/R) to the Center target (Ctr) for the graphs on the left, and movement was from the Left target (L) to the Center target (Ctr) for the graphs on the right. *Top graphs*: trials with real targets; *bottom graphs*: trials with virtual targets. Data from the 4 subjects are distinguished by symbol type: subject 1, ■; subject 2, □; subject 3. ●; subject 4, ○. Regression lines were drawn regardless of whether or not there was a significant relation (———: ■, ●; - - : □, ○).

We also looked for a relation between movement speed and curvature of the hand path. Averaged index of curvature values ranged from 4.2 (±0.2)% to 15.6 (±1.0)% for the various target combinations and subjects and did not differ significantly depending on whether the target was real or virtual (*t*-tests, $P > 0.05$). Regression results are summarized in Table 3. For the movement from the Up/R to the real Ctr target, only subject 3 had a significant speed effect ($P < 0.01$). In contrast, all subjects except subject 3 showed a significant speed effect ($P < 0.05$) for the movement from the Up/R to the virtual Ctr target. As was the case for the arm plane data, significant correlations could be negative or positive. In most (25/32) cases the regression coefficients were not significantly different from zero (parentheses in Table 3).

In one sense this lack of evidence for speed effects amounts to acceptance of the null hypothesis (that movement speed has no effect on final arm plane or path curvature). Therefore we computed the power of our statistical analyses to reject the null hypothesis when it is false (Zar 1996). In our analysis, we performed eight independent tests (four movements toward both virtual and real targets) of the null hypothesis for each subject and each dependent variable (final arm plane and path curvature). The average power for an individual subject ranged from 75 to 86%. However, because we performed eight independent tests with (scientifically) the same null hypothesis, the power of the entire analysis is greater than the power of any individual test. Thus we also used Fisher's combined probability test (Sokal and Rohlf 1995) and found that the combined power was >95%.

DISCUSSION

The current results are consistent with the idea that the control of reaching involves an optimization in the specification of the dynamic forces but not the antigravity forces. First, we showed that the dynamic-only prediction of Soechting et al. (1995) also held for "virtual" targets (i.e., targets removed and remembered just before the subject started to reach). More importantly we showed that, in contrast to the large, predictable effect of initial posture on final posture, there was no systematic effect of movement speed.

The optimization study of Soechting et al. (1995) was in the same spirit as others that minimized changes in torque, muscle force, or muscle activation (e.g., Alexander 1997; Uno et al. 1989; Yamaguchi et al. 1995). In most other experimental and optimization studies, the arm movement was confined to one plane, and thus the orientation of the plane of the arm was not a variable. On the other hand, the approach used by Soechting did not yield a prediction of hand-path curvature (as discussed by Soechting and Flanders 1998). Nevertheless, we confirmed that 3D curvature did not show any consistent variation with speed, in consonance with previous descriptions of speed invariance for 2D curvature (Atkeson and Hollerbach 1985; Flanders et al. 1996; Soechting and Lacquaniti 1981).

Kinetic optimizations such as those discussed above can be contrasted with results suggesting that kinematic features (e.g., hand path or joint angles) are under direct control. For example, the early results of Soechting and Flanders (1989a,b) suggested that arm posture (i.e., joint angles) at the end of a reaching movement is a simple function of 3D target location (a mapping between kinematic variables). These experiments included only one initial arm posture and one speed and therefore could not assess whether final posture was also influenced by other factors. When these same authors (Soechting et al. 1995) later showed a large effect of initial posture on final posture, there was a major difference between the two experiments; Soechting and Flanders (1989a,b) based their conclusions on the results of a virtual-target condition, whereas Soechting et al. (1995) used only real, visible targets. The current demonstration that predictions of Soechting et al. (1995) also apply to the virtual-target condition suggests that the conclusions of Soechting and Flanders (1989a,b) regarding the largely kinematic nature of a sensorimotor transformation should be amended to include a sizable influence of kinetic factors. Thus this conclusion is now seen to apply to both

TABLE 3. *Slopes of the relation between curvature of the path and peak velocity of the movement*

	Subject 1	Subject 2	Subject 3	Subject 4
Up/R → real Ctr	(−0.00)	(−0.02)	**−0.05**	(−0.00)
Up/R → virtual Ctr	−0.03	+0.02	(−0.03)	+0.03
L → real Ctr	(+0.00)	(−0.00)	(−0.02)	(+0.02)
L → virtual Ctr	(−0.22)	(+0.00)	(+0.00)	(+0.00)
Dwn/R → real Up/L	+0.02	**−0.03**	(+0.02)	(+0.00)
Dwn/R → virtual Up/L	(+0.02)	(−0.00)	(−0.02)	−0.02
Up/L → real Dwn/R	(−0.02)	(−0.00)	(−0.02)	(−0.02)
Up/L → virtual Dwn/R	(−0.02)	(−0.00)	(−0.00)	(−0.03)

Values are in %/cm/s. Entries in boldface are significant at $P < 0.01$; those in parentheses are not significant; others are significant at $P < 0.05$.

visually- and memory-guided pointing. Whether it is also true for movements that involve grasping remains to be determined.

Historically, the phenomenon of speed-invariant hand paths was taken as evidence for kinematic planning. If movement is planned and controlled as a series of static postures (Bizzi et al. 1992; Feldman 1966), time can simply be scaled to achieve a range of speeds. More recent work, however, suggests that force generation is also an important consideration in movement planning (Gomi and Kawato 1996) and may be subject to optimal control algorithms (Alexander 1997; Soechting and Flanders 1998; Soechting et al. 1995; Uno et al. 1989; Yamaguchi et al. 1995). However, we show here (Fig. 1) that, if the optimization algorithm is applied to the "total force package," this speed invariance is lost (see also Alexander 1997).

The apparent contradiction of conserved kinematics under force-based control might be reconciled by hypothesizing two separate force drives that can be separately scaled (Atkeson and Hollerbach 1985; Flanders and Herrmann 1992; Hollerbach and Flash 1982) and differentially optimized (Soechting et al. 1995) to achieve a family of invariant paths and postures at various speeds. One drive would control the antigravity torques, and the other would control the dynamic (speed-dependent) torques. However, in spite of this possible explanation, which drive(s) is (are) optimized and the exact nature of the optimization criterion (or criteria) have remained unresolved.

In this study, an optimal control scheme minimizing antigravity torques would predict that subjects should keep the plane of the arm near vertical (0 degrees in Figs. 2 and 3), regardless of the initial or final hand locations. Instead, subjects held the arm in a way that tended to minimize only the dynamic torques, as predicted by the optimization algorithm of Soechting et al. (1995). As shown in Fig. 1, if the two drives were together optimized (i.e., minimum dynamic + antigravity torques), the optimal solution would change with speed. This might be disadvantageous from the perspective of kinematic planning and control because the visual–spatial aspects of arm movements would change with speed (e.g., as movement becomes faster during learning). From this perspective it seems fortunate that only the dynamic solution appears to be optimized by the controller. This allows arm movements to exhibit the same spatial properties over a wide range of speeds.

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