16

Movement planning:
kinematics, dynamics, both or neither?

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16.1 Introduction

The path that the hand takes during a reaching movement is highly consistent from trial to trial. This is true for any one subject; it is also true across subjects (Georgopoulos, Kalaska & Massey, 1981; Soechting & Lacquaniti, 1981) and it is independent of the time it takes the hand to reach the target. Generally, the path of the hand is close to a straight line (Morasso, 1981), although there can be instances in which the hand path exhibits a considerable amount of curvature (Atkeson & Hollerbach 1985; Lacquaniti, Soechting & Terzuolo, 1986). Furthermore, the curvature of the hand path, cvcn when small is not arbitrary. For example, if one varies the direction of the movement from a fixed starting point (i.e. the now classic centre-out task introduced by Georgopoulos), one finds that the curvature varies in an orderly fashion with the direction of the movement (Flanders, Pellegrini & Geisler, 1996; Pellegrini & Flanders, 1996).

Theoretically, the hand could follow any number of paths to achieve a particular target. In fact, if an obstacle is placed in the way, subjects do alter the hand's trajectory to circumvent the obstruction (Abend, Bizzi & Morasso, 1982). Furthermore, if visual feedback is altered, a subject can be induced to alter the hand's trajectory. For example, if a distorted replica of the hand path is displayed on a computer monitor, a subject will alter the arm's trajectory over repeated trials so that the displayed path appears to be straight (Wolpert, Ghahramani & Jordan, 1994; 1995). Subjects can even be induced to produce hand paths that are straight when the paths are displayed in the space of joint angles, i.e. as a plot of elbow angle versus shoulder angle (Flanagan & Rao, 1995).

16.2 Movement planning

So the question arises: why do arm movements normally follow one particular trajectory and not any of the others that are possible? Since sub-
jects can in fact produce alternate trajectories, it is clear that the observed behavior results from constraints that reflect natural modes of neural processing. The question has generally been posed in the following manner: are movements planned in extrinsic coordinates (the path that the hand takes in extrapersonal space) or in intrinsic coordinates (the space of joint angles)? Underlying this question is a tacit assumption that has been borrowed from the field of robotics: movement planning and execution is a sequential process in which movement kinematics and dynamics* (or more precisely, kinetics) are expressed separately at different stages in the process (cf. Brady, 1982; Taylor, 1982). This assumption can be recast along the following lines: movements are planned at a kinematic level (in either joint or extrinsic coordinates) and, once such a plan of movement exists, forces adequate to produce the desired movement are first computed and then generated by the neuromuscular system.

16.3 The distinction between kinematics and dynamics

Why is it necessary even to make a distinction between kinematics and dynamics? In a one degree of freedom system, the force ‘F’ and the acceleration ‘A’ will be proportional to each other by Newton’s second law of motion and the distinction between the two is academic. This is not the case for the human arm, however, or any mechanical system with more than one degree of freedom. The force developed at the hand, if motion were to be impeded, is not parallel to the direction of the hand’s motion (Soechting & Flanders, 1992), nor are the torques at the shoulder and elbow proportional to the respective angular accelerations at the two joints. Thus, for the arm, there is a real distinction between kinematics and dynamics, the two being related through coupled nonlinear differential equations (Hollerbach & Flash, 1982). Given a desired motion of the hand, one can compute the torques that will produce it. Conversely, given a pattern of torques one can compute the motion of the hand that it will generate.

Given the distinction between kinematics and dynamics, the hypothesis that movements are planned at a kinematic level appears to be a reasonable one. However, other schemes have been proposed as well. Perhaps the one that is best known is the “equilibrium point hypothesis”, put forward in two different forms by Feldman (1986) and by Bizzi and his colleagues (Hogan et al., 1987). According to this hypothesis, the CNS controls muscle stiffness and muscle rest length (the length at which the muscle generates zero force) and by adjusting the values of these two parameters, the arm can be made to move from one resting state to another. Note that this hypothesis avoids the need to compute torques and muscles forces from

* Kinematics refers to a description of the displacements, velocities and accelerations of the motion whereas dynamics refers to the forces and torques that produce the motion.
kinematics and in fact, movement is no more than a progression of static postures. The merits of the hypothesis have been debated at length in a variety of forums (cf. commentary on Bizzi et al., 1992), and we will not repeat the various arguments here. Muscle stiffness must be appreciable for the hypothesis to be viable, especially for fast movements, and the best measurements to date (Bennett et al., 1992; Gomi & Kawato 1996) indicate that the actual stiffness is far below the values required by the "equilibrium point" hypothesis.

Neural network solutions for the control of reaching movements also avoid the need to separate kinematic and dynamic aspects of movement control. In this scheme, there is an input layer (typically encoding the location of the target and the starting posture of the hand, i.e. kinematics) and an output layer (typically encoding muscle forces). Given the properties of neural networks, however, the information encoded by "neurons" need not be related simply to any one particular parameter (Alexander et al., 1992; Robinson, 1992; but see Lukashin & Georgopoulos, 1993). Thus, one can envisage the possibility that kinematics are encoded by sensory receptors (the input level) and dynamics by the effectors (the output level), but that either kinematics or dynamics, or both, or neither are encoded anywhere in the brain circuits responsible for generating a goal-directed movement.

16.4 Optimality criteria

One way to make the question that we have posed at the outset of this chapter more tractable is to restate it in the following way: in what sense are arm movements optimized? The general procedure is to establish a "cost function" and then to compute the trajectory that minimizes that particular cost function (Nelson, 1983). At first glance, this approach seems far removed from the question: are movements planned at a kinematic or dynamic level. However, as we will show, the two approaches are equivalent to each other.

Consider for example neural network models. In this approach, the "synaptic weights" in the connections between the various levels are changed in an iterative manner to arrive at the ultimate solution. For example, the weights may be changed to minimize the errors at the end of the movement to targets distributed within a certain region of space. Note that in so doing, we have established an optimality criterion, namely to optimize movement accuracy. We could add other criteria as well: for example, to minimize the movement time or the distance that the arm moves, or the energy that is expended in moving the arm. Now some of these criteria, such as maximum accuracy or minimum time, do not lend themselves to a distinction between kinematic or dynamic planning. Others, such as minimum distance (kinematic) or minimum energy (kinetic), clearly do.
In fact, such an approach has provided the most compelling evidence in favor of movement planning at a kinematic level. Hogan and Flash (1987) proposed that arm motion was regulated so that the hand followed a trajectory that was maximally smooth, or to state it more precisely, that minimized jerk. According to this "minimum jerk" criterion, the hand should follow a straight path, with a bell-shaped velocity profile. In fact, the velocity profiles of hand trajectories generally do conform to this prediction. Recall however that hand paths, while often times being close to straight, nevertheless do exhibit curvature that is sometimes appreciable and is always predictable, contrary to the model. In the context of the equilibrium point hypothesis, Flash (1987) found a way around this dilemma by assuming that it was virtual trajectory that was optimally smooth, while the actual hand path was determined by muscle elasticity. Given sufficiently high values for muscle stiffness (and viscosity) this model was able to account for a wide range of experimental data.

Kawato and his colleagues (Uno, Kawato & Suzuki, 1989; Kawato et al., 1990; Dornay et al., 1996) also supposed that arm movements obeyed an optimality criterion, but one that was related to kinetics rather than to kinematics. In particular, they assumed that the rate of change of muscle torque was minimized ("minimum torque-change"), or more precisely, the integral over time of the sum of the squares of the rates of change of joint torques. The question arises: why the rate of change of torque and not the squares of the torques? The answer is that a "minimum torque" criterion has a solution where torque starts out with a large, positive (propulsive) value and ends with a large, negative (decelerative) value and changes smoothly between. (Similarly, a "minimum acceleration" criterion has large values of acceleration at the start and large values of deceleration at the end.) Experimentally, torques and accelerations build up gradually as the movement begins and they decay gradually as the movement is arrested. Consequently, minimum torque change" or a "minimum jerk" criteria are most parsimonious.

Uno et al., (1989) reported that the "minimum torque change" criterion was able to fit experimental data (Atkeson & Hollerbach, 1985) better than did the "minimum jerk" criterion described above. Subsequent work (Kawato et al., 1990) was aimed at demonstrating the biological feasibility of this approach by implementing the solution to this problem successfully in terms of a cascaded neural network. In order to fit the experimental data, these investigators needed to add a viscous term to the equations for the torques. Since the biological motivation for this adjustment is not immediate, the result is not as clear cut as it may appear at first glance.
16.5 Is the problem resolvable?

From the brief survey we have just given, it should be clear that the question "which parameters are the subject of movement planning"; has received a considerable amount of attention. Furthermore, it should also be evident that no clear answer has emerged. On a purely qualitative level, one finds straight hand paths, but one can also find instances of straight paths in joint space (cf. Soechting & Lacquaniti, 1981; Hollerbach & Atkeson, 1986; Shen & Poppele, 1995). Similarly, one finds adaptation to altered displays of movement kinematics in extrapersonal space or in joint space. Finally, quantitative models have given conflicting results.

Despite the slow progress on this problem, we argue that the question is a valid one. Furthermore, we argue that it is a well-posed question, as long as it is framed more precisely as: what parameter(s) is (are) optimized for arm movements? In the following sections, we will summarize some of our own recent work on this topic. We will present experimental data that indicate that kinetic considerations do indeed influence the trajectory of the arm, contradicting schemes in which movement planning is purely kinematic. We will also present the results of some modelling studies in which compare the relative importance of various "kinetic considerations".

16.6 Donders' Law and arm movements

According to Donders' Law, for any particular gaze direction, there is a unique orientation of the eyes (Nakayama & Balliet, 1977; Tweed & Vilis, 1990), independent of previous gaze directions. This is a powerful result and considerable work has been done to search for its neural substrates (cf. Crawford, 1994; Chapter 7 of this volume). From the perspective of this review, its significance is that it points to movement planning at the level of kinematics. Several investigators have tested the validity of Donders' Law for head and arm movements and have reported in the affirmative (Straumann et al., 1991; Hore, Watts & Vilis, 1992; Miller, Theeuwen & Giezen, 1992). Since arm movements were tested only under the very special condition of the fully extended arm, we wanted to know whether Donders' Law would also holds when there are varying degrees of flexion at the elbow (Soechting et al., 1995).

We found that it does not, but that we could account for the dependence of the final posture of the arm on its starting posture by a simple optimality criterion. In our task, subjects made pointing movements from one of 17 starting locations to five target locations arrayed throughout the three-dimensional workspace. The results from one subject are illustrated in Figure 16.1. The plots are arrayed in the same manner as the targets appeared to the subject: target 5 was in the middle, at shoulder level, target
Fig. 16.1. Arm posture at the end of a reaching movement depends on the initial posture of the arm. Subjects made reaching movements to 5 targets from each of 17 starting locations. The plots depict the average (± 1 SD) of the inclination of the plane of the arm for each of these combinations, from one subject. Note that for most of the targets, this parameter depends on the starting location.

3 was at the upper right, etc. In Figure 16.1 we show how the posture of the arm at each of the target locations varied as a function of the starting point of the movement. While there are four angles that are required to describe arm posture fully (three at the shoulder and one at the elbow), one variable suffices to characterize variations in arm posture with the hand at a particular location. We used the inclination of the plane defined by the upper arm and the forearm as this variable. Specifically, we computed the angle between the perpendicular to the arm plane and the horizontal plane and plotted the mean (±1 SD) of this angle in Figure 16.1.

If Donders' Law were obeyed, the inclination of the plane of the arm should not depend on the starting location of the movement. For Target 7, the one at the lower left, this prediction held. However, it did not hold true for the other four targets. For each of them, there was a statistically significant dependence of arm inclination on the starting location. Furthermore, the patterns were largely similar for the four subjects who were tested (see Figures 3 and 4, Soechting et al., 1995). We then set out to determine
whether we could account for the data by some simple criterion. Our initial hypothesis was one based on movement kinematics, namely that the final posture was the one that was closest to the starting posture, in the space of joint angles. The results did not conform to that hypothesis at all. In fact, when starting points and end points are plotted in joint space (Figure 5 of Soechting et al., 1995), one finds that there is no consistent relation between the two.

Other kinematic criteria were equally unpromising. However, finally we noted a characteristic that provided a clue to the answer: for some combinations of starting locations and target locations, the target could be acquired by simply rotating the arm about the long axis of the humerus. In fact, this is what the subjects did. The inertia of the upper arm is much less for rotations about the long axis of the humerus than it is for rotations about any other axis. Since joint torques are proportional to rotational inertia, this consideration suggests an optimality criterion based on kinetic rather than on kinematic considerations, for example the minimum torque change criterion mentioned above.

Generating predictions of the “minimum torque change” criterion is a considerable computational challenge for the case of a four-degree-of-freedom arm. Furthermore, from the point of view of testing the predictions of a model, we were primarily concerned with the final posture of the arm and less so with the path the arm took to get there. Accordingly, we developed a criterion that was much simpler computationally, but one that retained a kinship to the “minimum torque change” criterion. In particular, we developed a criterion based on the amount of work expended to move the arm from starting location to the target. Since work is equal to the change in kinetic energy, the total work is zero. (It is positive during acceleration and negative during deceleration.) Thus, total work done is not an appropriate criterion, but the peak positive work done during the movement could be. The peak positive work during the movement is equal to the peak kinetic energy, and this can be derived quite simply. (Soechting et al., 1995).

Figure 16.2 illustrates that this simple criterion was able to account for a large amount of the variability in the experimental data. In this illustration, we have combined the data for all four subjects, plotting the amount of humeral rotation (i.e. rotation about the long axis of the humerus) measured experimentally against the amount predicted by our “minimum peak work” criterion. Each of the symbols denotes a different target location. If the model’s predictions were satisfied, all of the data points should fall on a 45° line. Since this criterion was able to account for the data, whereas others that were based on purely kinematic considerations could not, we concluded that kinetic considerations influenced the final posture, and by inference, the arm’s trajectory. Thus, these results are not compatible with models in
which a purely kinematic plan of movement is formulated first, and then the requisite torques are computed.

16.7 Evaluating a minimum-torque-change model

The results presented in the previous section suggested that energetic considerations did have an influence on the arm's trajectory during pointing movements. The approach we used gave no predictions concerning the path however, only about the final posture of the arm. However, ultimately we hoped to gain some insight into what the advantages might be of moving along one particular path rather than another one. Simulation studies can be helpful in this regard, but the challenge of finding optimal solutions to the full four-degree of motion problem of the upper arm appeared too complex at the outset. Therefore, we began with a simpler case: planar motion of the arm, involving only two degrees of freedom - one at the shoulder and one at the elbow.

In particular, we considered the case of arm motion in a parasagittal plane, starting from a posture in which the upper arm is vertical and the forearm is horizontal. We considered motion to each of 20 targets arrayed around the perimeter of a circle centered at the hand. We chose this particular case because we had acquired a considerable amount of data concerning both
the kinematic patterns and the patterns of EMG activity that characterized movements to this set of targets (Flanders, 1991; Flanders, Pellegrini & Soechting, 1994; Flanders, Pellegrini & Geisler 1996). The hand paths from one subject are shown at the top of Figure 16.3. Note that the paths are gently curved and that most of them are curved in a clockwise direction. Paths directed to a quadrant that is centred about the upward direction, show the opposite curvature. This pattern is consistent from subject to subject (cf. Figure 16.6A).

There is also a consistent pattern of EMG activation. For relatively fast movements (i.e. movement times $\approx 400$ ms), EMG activity in individual muscles is similar to the pattern for single joint movements, namely a burst of activity either around movement onset (agonist) or around the time the movement has reached its peak speed (antagonist). However, the timing of these bursts is not consistent from muscle to muscle. For any given muscle, the timing varies in a continuous manner with the direction of the movement (Flanders, Pellegrini & Geisler, 1996).

Simulation studies by Buneo et al. (1995) suggest that these two phenomena (hand path curvature and staggered timing of EMG bursts) are linked. They computed shoulder and elbow torques for hypothetical straight movements and found that the timing of the maxima and minima of the torques did not vary with movement direction. Such a temporal invariance is not found experimentally, however, as can be appreciated in the lower part of Figure 16.3 which shows contour plots of shoulder and elbow torques for one subject (Soechting & Flanders, 1997). The comparison of simulations and experimental results suggests that subjects could in fact generate straight movements if only they could activate synergistic muscles in unison. Since it is commonly believed that muscles synergies lead to a simplification of the control problem (cf. Macpherson, 1991), one is left with the quandary that subjects appear to invoke a control strategy that is more complicated than it would need to be. Clearly there should be some advantage to the experimentally observed trajectories that makes up for the increased complexity. Saving energy is a likely candidate.

Therefore, we began by computing the hand paths that would satisfy the “minimum torque change criterion” Specifically we computed trajectories for which

$$J = \int [(dT_s/\Delta t)^2 + (dT_e/\Delta t)^2] dt$$

(16.1)

was a minimum. The shoulder and elbow torques ($T_s$ and $T_e$) were computed from the angular motions at the shoulder and elbow. The motions in turn were computed from the path of the hand, using trigonometry. Thus, the procedure was to vary the hand’s trajectory and finding the particular trajectory for which $J$ was a minimum, keeping the movement time fixed. Specifically, we defined $x$ as the distance along a straight line from the start
Fig. 16.3. Hand paths and joint torques during reaching movements. The top panel depicts hand paths for reaching movements to 20 targets spaced at 18° intervals on the circumference on a circle. The movements were performed with the arm in a parasagittal plane, starting with the upper arm vertical and the forearm horizontal. Note the curvature of the hand paths. The lower two panels depict contour plots of the temporal variation in shoulder and elbow torques for these movements. In these plots, time increases starting from the center. The inner white circle denotes the time of movement onset and the second circle denotes the midpoint of the movement (200 ms later).

to the target and \( y \) as perpendicular to \( x \). We then used polynomials in time to characterize the movement of the hand:

\[
\begin{align*}
x(t) &= P(t) \\
y(t) &= P(t)s(t)
\end{align*}
\]  

(16.2)

where \( P(t) \) and \( s(t) \) are polynomials, subject to

\[
\begin{align*}
P(0) &= dP(0)/dt = dP(T)/dt = 0 \\
P(T) &= D \\
s(0) &= s(T) = 0
\end{align*}
\]

(16.3)

where \( T \) is the movement time and \( D \) the distance from the start to the target. We used an iterative procedure (Nelder & Mead, 1964; see also Press et al., 1992) to find the coefficients of the polynomial that minimized
Fig. 16.4. Predictions of the "minimum torque change" criterion. The format of this figure is the same as that of Figure 16.3. In this simulation, hand paths and torques were computed based on the criterion that the rate of change of torque at the shoulder and elbow was minimized. The components of the torques that counteract the effects of gravity were not included in this simulation.

J. We used five terms for $P$ (beginning with $a_P t^2$) and four terms for $s$ (beginning with $a_s t$). There were six independent variables, the other three coefficients being determined by the boundary conditions (equation 16.3).

Figure 16.4 illustrates the results of this simulation. In this instance, we did not include the gravitational contributions to the shoulder and elbow torques because previous research had suggested that the static (gravitational) and the dynamic (speed-related) components of muscle activations were controlled separately (Flanders & Herrmann, 1992). The model clearly does not match the experimental data (Figure 16.3). The hand path curvatures predicted by the "minimum torque change" criterion were generally much larger than the experimental ones. Even worse, for most of the movement directions, the paths curved in the wrong direction. This can also be appreciated by comparing the results in Figure 16.6B with those in Figure 16.6A.

The fact that we ignored the static (gravitational) torque components did not account for the discrepancy between the model and the experimental
Movement planning

data. We repeated the simulation, now including gravitational torques, for a movement time of 400 ms and found almost exactly the same hand paths as those shown in Figure 16.4 (compare heavy and light lines in Figure 16.6B).

An examination of the torque profiles (lower part of Figure 16.4) provided a suggestion as to why the model failed. Note that for movements directed slightly backward and upward and slightly forward and downward, there is little modulation in shoulder torque for the optimal hand paths. Similarly, for movements directed slightly upward and forward or slightly downward and backward there is little modulation in elbow torque. That is to say, the shoulder and elbow torques are modulated maximally in approximately orthogonal directions. For the experimental data (Figure 16.3), shoulder and elbow torques are much more congruent. The pattern predicted by the model (Figure 16.4) could be implemented economically by mono-articular muscles, but bi-articular muscles (such as biceps and the long head of triceps) could not be used effectively to generate the motions depicted in Figure 16.4. This is because, when a bi-articular muscle is recruited to generate shoulder torque, its action at the elbow would have to be negated by monoarticular antagonists, such as brachioradialis and the medial or lateral head of triceps. A similar situation would hold for movement directions in which a large amount of elbow torque is required.

This observation suggested that an appropriate optimality criterion would have to be applied at the level of muscle forces, rather than for the overall torques generated at each joint. We set out to test the viability of this hypothesis by additional simulations. A realistic model, that incorporated all the major muscles acting at the shoulder and elbow, and also the viscoelastic properties of muscles (Soechting and Flanders 1997) appeared to be too complicated to implement. However, the techniques that we used to generate the predictions in Figure 16.4 could be extended readily to a simpler model, restricted to only six muscles (a mono-articular agonist/antagonist pair at the shoulder and elbow and bi-articular muscles). This model ignored muscle viscoelasticity (Zajac, 1989), but did incorporate muscle geometry, i.e. the effective insertions and origins of each of the muscles (Wood, Meek & Jacobsen, 1989; Buneo, Soechting & Flanders, 1997).

If there are only six muscles, as in our model, one can obtain a unique solution for the distribution of force among the muscles that minimizes the sum of the squares of muscle forces, $F_m$. First of all, this criterion predicts there should be no muscle coactivation. Therefore, for any combination of shoulder and elbow torques, one need only take into account three muscles. For example, if there is flexor torque at the shoulder and elbow, one need only consider anterior deltoid, biceps and brachioradialis - forces in the shoulder and elbow extensors (posterior deltoid, and the long and medial head of triceps) should be zero. Then, for the three remaining muscles, there
is a unique analytical solution for which

\[ J = \sum F_m^2 \]  \hspace{1cm} (16.4)

is a minimum. Accordingly, this model required only small changes to the procedures we had used to find the optimal hand path. We again did an iterative search, first defining a hand path, then computing shoulder and elbow torques for that path, then the corresponding muscle forces and finally the criterion to be minimized:

\[ J = \int \sum (dF_m/dt)^2 dt \]  \hspace{1cm} (16.5)

Figure 16.5 shows the results of this simulation for the case in which gravitational torques are excluded. These results were much more encouraging in that the predicted hand paths resembled much more closely the experimental data than did the joint torque model. Generally, the paths were much straighter. Furthermore, for most paths, the curvature was in the correct
Fig. 16.6. Variations in hand path curvature. The panels depict: A) experimental data for four subjects, B) the results of simulations based on the “minimum torque change” criterion, and C) and D) the predictions based on the minimum “muscle force change” criterion. In each case the heavy line shows results in which gravitational effects were included; the lighter line shows results in which gravitational effects were not included. Curvature was computed as the ratio of the maximum deviation from a straight path to the path length (see Pellegrini & Flanders, 1996 for details).

direction (compare Figure 16.6C with Figure 16.6A). While one would be reluctant to take the results as proof of the model’s validity, neither is there an inducement to reject the model outright (especially in view of the major simplifications introduced in the analysis).

We performed one additional simulation, in which we included static (gravitational) torques in the minimum muscle force change model. The results of this simulation (Figure 16.6D) were very similar to those obtained from the minimum torque change model, that is to say, they did not fit the experimental data at all. This observation is consonant with experimental data that suggest that static (gravitational, speed-insensitive) and dynamic (speed-sensitive) components of muscle torques are controlled separately and that only the dynamic components influence the selection of the arm trajectory (Flanders & Herrmann, 1992; Soechting et al., 1995).
16.8 Conclusion

We have shown that the final posture of the arm in a reaching movement can be predicted according to a criterion that is related to energy expenditure (minimum peak work) and that the hand paths during planar arm movements can be at least partly predicted by another criterion (minimum muscle force change) that is also related to energy expenditure. There are differences between the two models - the major one being that the simulations related to arm posture at the end of a pointing movement (Figure 16.2) reflected global parameters (such as joint torque) whereas the second set of simulations indicated that an evaluation of energy expenditure that is muscle-based would be more appropriate. We do not know whether or not a muscle-based criterion could also account for the variations in arm posture depicted in Figure 16.1.

In both instances, we made major simplifying assumptions. We did so because more realistic models that more accurately reflected muscle properties such as force-velocity and length-tension would have made the analysis computationally intractable. We also refrained from making the models more complicated because there is a large amount of uncertainty in the values of many of the parameters needed to characterize the properties of each of the muscles. Nevertheless, with regard to the question that we posed in the title of this article, we believe that we have demonstrated that movement planning involves more than just kinematics. That is to say, the data are not compatible with a scheme whereby movement kinematics are worked out first, and then the required torques and muscle forces are computed. Rather, movement planning must involve dynamics.

Does movement planning involve kinematics, as well? Of course! Consider for example the case where there are obstacles in the path. Clearly, the hand path must be planned to avoid the obstacle. But what if the obstacle impedes the motion of the elbow, but not the hand? We have no difficulty altering the configuration of our arm to avoid such obstacles. Thus kinematic planning can't be restricted purely to the trajectory of the hand (i.e. its motion in extrapersonal space), but must be concerned with the angular motion at each of the joints as well. What if there are no obstacles? In all of the movements that have been studied, the hand moves in a fairly direct path towards the target. It would be incorrect to characterize the motion as rectilinear but it would also be incorrect to characterize it as being highly curved. It is not unreasonable to suggest minimizing path length is part of the plan for a movement.

This discourse suggests that the answer to the title question is “both”. Could it be “neither”? We cannot exclude that possibility, but we have trouble finding some criterion that is not related to kinematics or to kinetics. Certainly, the fact that individual subjects make movements that are highly
consistent from one trial to another and the fact that many of these characteristics are preserved from one subject to another suggest that there are strong constraints that shape the manner in which movements are normally performed. We suggest that these constraints can be defined by optimality criteria, but there is no one single such criterion that determines behavior.

Acknowledgments

This work was supported by USPHS Grants NS 15018 (JFS) and NS 27484 (MF).

References


