Planning Reaching and Grasping Movements: Theoretical Premises and Practical Implications

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This paper presents the background, premises, and results of a model of movement planning. The model's central claims are fourfold: (a) A task is defined by a set of prioritized requirements, or what we call a constraint hierarchy; (b) movement planning works first by specifying a goal posture and then by specifying a movement to that goal posture; (c) movements have characteristic forms; and (d) movements can be shaped through simultaneous performance of different movements, even by the same effector. We review the model and then speculate on its implications for clinical concerns, especially spasticity.

Key Words: motor planning, computational model, posture, reaching, grasping, prehension

Introduction

In a well known photograph of Albert Einstein riding a bicycle, Einstein looks like an ebullient child cycling for the first time. The picture reminds us that even those adept at articulating physical principles may find it hard to say how those principles are exploited in everyday life. (To the best of our knowledge, Einstein never wrote about how he cycled.) The photograph also reminds us that even basic research may come to have important applications. Einstein's theories influenced the development of modern electronics and weaponry. Conceivably, basic research on the control of movement could likewise have practical applications in such fields as robotics, computer animation, athletics, the performance arts, and medicine.

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Using Einstein's picture to make this point is not meant to imply a comparison between the present authors and the 20th century's greatest physicist, nor to suggest that the practical spin-offs of our theorizing will be as dramatic as Einstein's were. The charm of the picture merely helps set the stage for the arguments to come. In this article we will first review the problem we have aimed to solve, then we will describe the model we have developed to solve it. Next we will present some of the model's results, and finally we will discuss other issues to be confronted by the model, including applications to clinical issues such as spasticity.

The Problem

The problem we have studied is how a particular reaching movement is selected for a task when many reaching movements allow the task to be completed. Consider the task of reaching for the off switch of a rotating electric saw. There are many ways to perform this task, and some are clearly better than others. How is the chosen reach selected?

We can address this question by considering cartoons (Figure 1) showing a stick figure capable of bending at the hip, shoulder, and elbow to make reaches in the sagittal plane. If the stick figure needs to touch a point at the edge of its workspace (panel A), it can do so with only one body configuration. However, if the point lies inside the workspace, different postures can be used to bring the hand in contact with the point, as shown in panels B, C, and D. In general, for a point within the workspace, an infinite number of postures allow the hand to reach that point and, by extension, an infinite number of postures can be adopted on the way. Hence, a choice problem attends the ostensibly trivial problem of touching a point in space: Infinitely many final positions may be adopted, each of which may be reached through infinitely many paths. Given this plethora of options, how is a particular movement chosen?

Posture-Based Motion Planning

The model we have developed to answer this question focuses on posture-based motion planning. The model makes four general claims:

1. A task is defined by a set of prioritized requirements, or what we call a constraint hierarchy.
2. Movement planning works by first specifying a goal posture and then by specifying a movement to that goal posture.
3. Movements have characteristic forms.
4. Movements can be shaped through superposition.

We elaborate on these claims below.

Constraint Hierarchy

When we use the term constraint hierarchy, we refer to a set of requirements ranked from most to least important. One reason for positing the constraint hierarchy is to answer a deceptively simple question: "What is a task?" There has been great emphasis on task-based solutions (Saltzman & Kelso, 1987) and the idea, which we endorse, that actions are tuned to the tasks actors undertake. As sensible as the

Figure 1 — Stick figure capable of bending at the hip, shoulder, and elbow to make reaches in the sagittal plane to a point at the edge of the workspace (A) or to another point within the workspace (B–D). Reprinted from Rosenbaum, D.A., & Engelbrecht, S.E., Bushe, M.M., & Loukopoulos, L.D. (1993b). Knowledge model for selecting and producing reaching movements. Journal of Motor Behavior, 25, 217-227.
movements to goal postures are generated de novo. The fact that memory for end-positions is better than memory for movements (see Smyth, 1984), be performed.

A second reason for considering the goal-posture-first hypothesis is that direct neuro-physiological evidence for planning backward from end states to earlier states has been obtained. Ashe et al. (1993) found that when a monkey had to move a lever forward and then to the left, the population vector of its motor cortex cells initially shifted in the direction of the second position and only later shifted in the direction of the first position. This outcome led Gazzaniga, Ivry, and Magnun (1998), in commenting on Ashe et al.'s finding, to conclude that "the motor plan unfolded in the reverse order of the actual movements" (p. 392).

Movement Regularity

The third claim of our model is that movements have characteristic forms. It is well known that movements are sufficiently stereotyped with respect to identifiable physical features (e.g., smoothness and approximate symmetry of speed profiles) that a number of movement scientists have suggested that all movements (or at least all manual positioning movements) might satisfy some physical constraint defined by such a feature—for example, minimization of jerk (Flash & Hogan, 1985) or minimization of mean torque change (Uno, Kawato, & Suzuki, 1989).

Even if the constraint-hierarchy hypothesis says that no single constraint accounts for all movement choices, movement regularity is likely to allow for minimization of end-state variability, as needed for movement positioning (Harris & Wolpert, 1998). Movement regularity also provides a way of generating lifelike movements in computer simulations, which can be helpful in applied contexts. In the simulations summarized here, the joints' angular velocities were assumed to be symmetric bell-shaped functions of time and thus reflected a minimum jerk principle for angular displacements (see Nakano et al., 1999, for supporting evidence).

A final point about movement regularity is that if movements can be optimized with respect to some variable such as minimum jerk, this provides yet an-
other, albeit indirect, source of support for the view that goal postures are specified before movements. The reason is that if a movement is optimized with respect to jerk or one of the other optimization variables that has been considered in the motor control literature—for example, minimization of torque change (Uno et al., 1989) or minimization of peak work (Soechting, Buneo, Herrmann, & Flanders, 1995)—the movement’s final position must be known in advance to carry out the necessary calculations.

We note that if movements have well-defined regularities, this certainly does not mean that the regularities were explicitly specified in advance by the motor planning system. Instead, the regularities could emerge as a result of physical properties of the effectors in interaction with the external environment.

**Shaping of Movement Through Superposition**

Our model allows for the fact that movements to the same end position can be shaped according to task demands. Shaping of movements is needed in tasks such as drawing desired curves or reaching around obstacles. The way movement shaping occurs in our model is through internal simulation of possible movements to check their likely consequences, followed by alteration of the initially planned movement path if necessary and if time permits. Allowing for internal movement simulation is consistent with a great deal of recent research emphasizing the role of forward modeling in perceptual-motor integration (Duhamel, Colby, & Goldberg, 1992; Miall, Weir, Wolpert, & Stein, 1993; Wolpert, Ghahramani, & Jordan, 1995).

The way our model allows for the shaping of movement trajectories is by allowing for simultaneous movements, even by the same effector. In the case of writing, the pen tip is aimed to points of maximum graphic curvature through points of minimum graphic curvature (Meulenbroek, Rosenbaum, Thomassen, Loukopoulos, & Vaughan, 1996). For the writing to be smooth, these writing strokes are cascaded so the stroke to target n can begin while the stroke to target n - 1 is in progress. This method has been used before (Edelman & Flash, 1987).

Another way to shape movements using our computational model is by allowing for more complete overlap of movements. As described in Rosenbaum et al. (in press), one movement can be made from the starting posture to a goal posture (the main movement), while another movement proceeds from the start posture to a via posture and then back to the start posture. The latter series of movements adds no net displacement to the overall trajectory but makes the movement more or less circuitous depending on which via posture is used. The possibility of simultaneously performing different movements with the same effector has been suggested before (Feldman, 1980; Flash & Henis, 1991; Mussa-Ivaldi, Giszter, & Bizzi, 1994; von Holst, 1939/1979), but the application of this method to obstacle avoidance and path shaping for graphic performance has not, as far as we know.

**More Computational Details**

Having sketched the main claims of our model, we now give more specifics about its implementation. The model has been rendered in a series of computer simulations (Meulenbroek et al., 1996; Rosenbaum et al., 1993a, 1993b, 1995; Rosenbaum, Loukopoulos, Engelbrecht, Meulenbroek, & Vaughan, 1996; Rosenbaum, Meulenbroek, & Vaughan, 1996; Rosenbaum, Meulenbroek, & Vaughan, 1999; Rosenbaum, Meulenbroek, Vaughan, & Elsinger, 1999; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 1999). Technical details appear in Rosenbaum et al. (in press), and applications of the computations to obstacle avoidance and grasping are described in this volume by Vaughan et al. and Meulenbroek et al.

Our model relies on stored postures from recently performed tasks. When a task needs to be performed, a search is carried out for the most promising goal posture from among the stored posture set. Which stored posture is most promising is defined with respect to the constraint hierarchy. In most of the reaching tasks we have modeled, collision avoidance is the highest priority, spatial accuracy (i.e., contact with the target object) is the next highest priority, and effort reduction is the lowest priority.

Even with a constraint hierarchy and a large set of stored postures, there is no guarantee that a previously stored goal posture will allow a task to be performed. This is because the positions of to-be-reached objects constantly change, and actors' bodies also change as a result of growth, limb loss, weight change, and new attachments to or extensions of the body (e.g., bulky clothes or hand-held tools).

The way our model solves the need for novel goal postures is as follows. After the most promising stored posture is found, a search is undertaken around it in posture space. Postures are generated in the region of the most promising stored posture and are evaluated with respect to the constraint hierarchy. This process of generating and evaluating candidate goal postures continues until a deadline is reached, at which time the best of all the considered postures is identified as the goal posture. The best considered posture is the one that satisfied the most constraints, from most to least important. If there is a tie for best posture, the tie is broken randomly.

Once the goal posture is found, some further “book-keeping” is done to establish the deadline for the next trial. The deadline goes down toward a minimum of 1 if the best posture was found before the current deadline, or goes up toward a maximum value related to the grain size of posture space if the best posture was found at the current deadline (see Rosenbaum et al., in press, for details). To keep the posture store from overflowing, only the last m goal postures are stored, where m is a parameter corresponding to the size of the posture store. (In most of our simulations, m was less than 10.)

The model’s default movement from the start posture to the goal posture follows a straight line in posture (or joint) space. It is known that not all movements are linear in joint or extrinsic space (e.g., Haggard & Richardson, 1996), so the straight-line assumption is a simplification. However, all models are simplifications by definition, and if the linearity assumption is wrong, its incorrectness is possibly due to the fact that the model is so far restricted to kinematics (i.e., consideration of positions without regard to the forces behind them). See Flash and Hogan (1985) for a similar argument.

A desirable feature of straight-line movement from the start posture to the goal posture is that this method can be viewed as shortest-path interpolation between the start and goal postures. The spacing of successively adopted positions along the interpolation path used in our model permits bell-shaped angular velocity profiles (see Rosenbaum et al., in press, for details, and Nakano et al., 1999, for evidence supporting the view that angular velocity profiles are bell-shaped).

Another desirable feature of the movement-as-interpolation approach is that it can easily extend to movements in three spatial dimensions rather than two. Consider, by contrast, a movement-based planning system (i.e., one for which
positions follow rather than precede movements in planning). Here, the order in which movements are tried out can have unexpected effects when the joints rotate in three-space. This is because joint rotations are non-commutative: The order in which joints rotate affect limb end position (Gielen, Vrijenhoek, & Flash, 1997).

In a posture-based planning system (i.e., one for which end positions precede rather than follow movements in planning), this is not a source of concern because posture-based motion planning treats movements as interpolations between already known start and end postures.

Straight-line motion from the start to the end posture can serve as the default movement, but when further shaping of the movement is necessary, a via posture must be found. Because the via posture is the posture to which one moves from the start posture and then returns while the main movement is proceeding from the start posture to the goal posture, the identity of the via posture affects the curvature but not the end position of the movement path. The way the via posture is found is similar to the way the goal posture is found. The constraint hierarchy is altered only slightly to allow for its identification. Details of the method are described in Rosenbaum et al. (in press) and Vaughan et al. (this volume).

Simulations

The ideas expressed above constitute a set of hypotheses about the planning of limb positioning movements. To evaluate the hypothesis, we have run computer simulations and conducted behavioral experiments. The computer simulations have forced us to make our assumptions explicit (Hintzman, 1991) and have helped us see whether our proposed ideas are tenable. In the following, we focus on simulation results. Behavioral tests of the model have appeared in other papers (Fischer et al., 1997; Rosenbaum, Meulenbroek, & Vaughan, 1999; Rosenbaum et al., in press; Rogosky & Rosenbaum, 2000; Vaughan et al., 1998). The simulation results that follow comprise a subset of those we have generated. New simulations especially relevant to the themes of this volume appear in the two articles following this one.

Pointing and Compensating for Changes in Joint Mobility

Many of our simulations involve a stick figure that bends at the hip, shoulder, and elbow in the sagittal plane. Figure 2 shows that the stick figure can reach spatial targets within the workspace from other positions. The movements look compelling when viewed in real time. (The computer simulation described here is available as an executable, PC-compatible program that can be downloaded from the second author's homepage <http://www.socsci.kun.nl/~meulenbroek/>.)

A simulation result that is potentially very important for clinical applications is that the stick figure can compensate immediately for changes in joint mobility, as shown in Figure 3. This series of images shows three cases in which the stick figure starts in the same position (sitting with its arm fully extended) and must always bring its hand to the same point (in front of its knee). The top panel shows a normal movement, the middle panel shows movement when it is difficult to bend the elbow, and the bottom panel shows movement when it is difficult to bend the hip. Difficulty of bending a given joint is expressed in our model by the joint's expense factor. The idea behind the expense factor is that when the expense for a joint is high, goal postures that require large rotations of that joint are disfavored, whereas goal postures that require large rotations of other joints are favored. It was on the basis of this idea that the simulations in Figure 3 were generated. To generate the simulations, we simply increased one number—the expense factor for the elbow in Figure 3B, or the expense factor for the hip in Figure 3C—and the stick figure immediately altered its movement. To our knowledge, this is the simplest solution proposed so far for the problem of compensating for changes in joint mobility (cf. Mussa-Ivaldi, Morasso, & Zaccaria, 1988).

Reaching Around Obstacles

Reaching around obstacles is an important problem in everyday life, as emphasized in the article by Vaughan et al. (this volume). The centrality of obstacle avoidance is illustrated in the photograph shown in Figure 4, which comes from Rumelhart and McClelland's (1986) Parallel Distributed Processing. This figure shows Jay McClelland's hand as he reached around his computer for a cup of coffee. Rumelhart and McClelland used reaching around obstacles to illustrate multiple constraint satisfaction problems, which lie at the heart of cognitive science. These authors indicated that if the obstacle-avoidance problem could be solved, one might say that a significant obstacle had been overcome in the advancement of cognitive science.

The obstacle-avoidance problem is difficult because it is a thorny ontological problem to say what an obstacle is. An obstacle need not be an object in the external environment. One's own head can be an obstacle when one touches the left ear with one's right hand or vice versa. Similarly, if one wants to tie one's shoe while sitting on a chair, one's own leg may need to be circumvented. Thus, an obstacle to motion may even be a part of one's own body. Given the ontological problem of saying what an obstacle is, it turns out that an especially profitable way of identifying obstacles is by characterizing them as "bad postures"—that is, postures which, if adopted, would spatially overlap with objects to be avoided (Lozano-Perez, 1983). The problem of saying what an obstacle is can be addressed then, by defining obstacles with respect to postures, which is yet another argument for posture-based motion planning.

Simulated reaches around obstacles and related issues are discussed by Vaughan et al. (this volume). An example of grasping an object after circumventing another one is shown in Figure 5. This simulation was achieved by using the ideas outlined earlier in this article.

Figure 3 — Compensation for increases in expense factor for rotation of the elbow (middle panel) and the hip (bottom panel) compared to normal expense factors (top panel). The starting posture (reaching fully forward) is the same in all three panels, as is the spatial target (just in front of the knee). Reprinted from Rosenbaum, D.A., Loukopoulos, L.D., Meulenbroek, R.G., Vaughan, J., & Engelbrecht, S.E. (1995). Planning reaches by evaluating stored postures. Psychological Review, 102, 28-67.

Writing With Different Effectors

Figure 6 shows the last simulation presented here. This figure shows writing of the cursive letter f in the horizontal and sagittal planes (Meulenbroek et al., 1996). The written output is more or less the same in the two cases, as are the pen-tip kinematics. Nonetheless, the angular velocity profiles of the joints in the two simulations are entirely different. This outcome shows that the model provides a basis for solving the long-standing problem of motor equivalence in graphic performance. The problem is to explain how one can achieve the same graphic output through different motoric means. Our analysis suggests that the answer may inhere in specifications of spatial locations to which and through which pen strokes are made, using specification of goal postures followed by specification and then generation of movements. (Another possibility is to generate writing by combining movements to and from via postures with movements to goal postures from via postures.) The fact that our model achieves motor equivalence does not prove that its methods are used by the nervous system but the success of the method provides prima facie support for its plausibility.


Speculations About Motor Disorders

Although our model still needs further validation and elaboration, its preliminary success encourages us to contemplate its clinical implications. Can the model shed light on movement disorders? Because the model's focus is normal motor planning, it should predict what happens when movement planning and execution work correctly. Similarly, when the model is degraded, its planning and performance should go awry. The usefulness of the model for clinical purposes can be judged by whether its lapses map onto clinically observed deficiencies.

It is useful in this context to consider the main components of the model and then to ask what would happen if one or more of them were disrupted. Some general predictions can be sketched.

1. If the range of motion of one or more joints were acutely smaller than normal or if the expense factors for one or more joints were acutely higher than normal, joints that have normal movement capabilities would be used more than they usually are. This outcome has already been shown (Figure 2) but bears repeating because the result of reduced mobility in one or more joints would not, by itself, reflect a motor planning deficit per se. Instead, the capacity for greater-than-normal use of normally functioning joints would be indicative of normal planning. In this connection, it is instructive that individuals with hemi-spasticity appear to be normal in tests of motor planning (Steinbergen, Hulstijn, & Dortmans, in press). The fact that the model can be used to show that seemingly abnormal movement is not due to abnormal motor planning helps validate claims by Latash and Anson (1996) that some movement "disorders" are in fact highly adaptive given peripheral neuromuscular constraints.

2. The model assumes a posture store, which may of course be damaged. The capacity for storing new postures may be impaired, the capacity for holding older postures may be disrupted, and either or both of these problems may affect specific types of postures (e.g., postures of the left arm only) or any types of posture. Restrictions of movement, including those seen in spasticity, may be ascribed to posture storage problems.

3. If the capacity to generate via postures were impaired, trajectory shaping would suffer. Because in our model extra planning is required for deliberate shaping of movement paths, one might expect to see breakdowns of complex trajectory generation per se. Such breakdowns would also be expected if movement superposition could not be achieved for some reason.

4. The model assumes a constraint hierarchy defining the task to be performed. Breakdowns in the formation of constraint hierarchies could lead to disruptions of motor planning. Apraxia might be one manifestation of constraint hierarchy malformations.

These ideas are developed further in the two articles to follow this one. An important caveat about the application of the model to motor disorders is that the model has only been concerned with kinematics and has only permitted motion in man. Neuroscience, 5, 81-90.


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