Motor Control, 2001, 2, 116-135

Planning Reaching and Grasping Movements: The Problem of Obstacle Avoidance

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In this article, we review a model of the movement-planning processes that people use for direct reaching, reaching around obstacles, and grasping, and we present observations of subjects' repeated movements of the hand to touch 2 target locations, circumventing an intervening obstacle. The model defines an obstacle as a posture that, if adopted, would intersect with any part of the environment (including the actor himself or herself). The model finds a trajectory that is likely to bring the end-effector to the target by means of a one- or two-stage planning process. Each stage exploits the principles of instance retrieval and instance generation. In the first stage, a goal posture is identified, and the trajectory of a direct transition to that posture is tested for collision. If that direct movement has no collision, the movement to the target is immediately executed in joint space. If, however, the direct movement is foreseen to result in a collision, a second planning stage is invoked. The second planning stage identifies a via posture, movement through which will probably avoid the collision. Movement to and from the via posture is then superimposed on the main movement to the target so that the combined movement reaches the target without colliding with intervening obstacles. We describe the details of instance retrieval and instance generation for each of these planning stages and compare the model's performance with the observed kinematics of direct movements as well as movements around an obstacle. Then we suggest how the model might contribute to the study of movements in people with motor disorders such as spastic hemiparesis.

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

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Introduction

Reaching a target in external space (e.g., picking up a salt shaker) requires movement of an end-effector such as a hand or a tool to a target location. If the target is within the bounds of reachable space rather than at or beyond the bounds, any of an infinite number of goal postures can accomplish this task, and any of an infinite number of movements to any of those goal postures may suffice as well (Bernstein, 1967). The movement may proceed directly from the start posture to the goal posture, but if there are any potential obstacles, the direct movement may result in collision with one or more of them. Reaching around the obstacle (e.g., grabbing the salt without spilling one's milk) requires selecting one out of an infinite number of possible indirect trajectories to the goal posture. Planning a more complex movement such as grasping an object may also be viewed as requiring movement to a posture that encloses the object without colliding with it along the way (Meulenbroek, Rosenbaum, & Vaughan, 2001). Thus, a model of obstacle avoidance is of potentially wide application in the understanding of motor behavior.

As the last example shows, intelligent choices must be made about when contact can and cannot be made with external objects. It is acceptable to contact the object with the inside of the hand once it is graspable but not to contact the object with the outside of the hand beforehand. A model must be able to explain such intelligence in motor behavior. Here we describe one such model and evaluate it by simulating performance in the everyday task of obstacle circumvention.

Planning Reaches

The model to be described has been presented elsewhere in some detail (Rosenbaum, Meulenbroek, & Vaughan, 2001; Rosenbaum, Meulenbroek, Vaughan, & Jansen, in press). To review briefly, according to the model, a task to be performed is defined by a set of constraints. Thus, for example, the task of reaching to touch an object requires adopting a posture that brings the hand in contact with the object, moving in an efficient manner, and not colliding with any obstacles along the way from the starting posture to the target posture. To reach a new target, the model identifies a candidate goal posture from previously known postures, selecting one of the stored postures that most nearly accomplishes the task. Next, the model generates new postures near this candidate goal posture in order to identify another posture that is potentially more effective. Because the model is purely kinematic (solely for convenience), and because the most direct transition from one posture (a vector of joint angles) to another can be found in joint space, the operation is done by an orderly search of neighboring postures within joint space. The search continues until an adjustable planning deadline has elapsed, at which time the best goal posture so far identified is adopted as the goal posture.

The movement from the starting to the goal posture is planned next. By default, the movement is a straight-line trajectory in joint space, although as will be seen below, the default movement can be modified when the trajectory must be shaped differently, as when an obstacle intervenes. Finally, the movement is performed and the planning deadline for subsequent actions is either lengthened (if more planning time might have improved the effective reach in this instance) or shortened (if less extensive planning might have sufficed).

Goal Posture and Trajectory Planning When There Is No Obstacle

Planning a reach when there is no obstacle involves four steps (Table 1). Step 1 is identifying, from among the stored postures, a candidate goal posture (*instance retrieval*, in Logan's, 1988, terms). In Step 2, the model generates variations on the candidate goal posture through joint space (Logan's *instance generation*). Each posture variation is evaluated with respect to the constraints that define the task (e.g., accuracy and movement efficiency for simple reaching). Any variation that better meets the constraints becomes the provisional goal posture. In this step an efficiency constraint is evaluated by computing the weighted sum of the joint rotations required for transition from the starting posture to the goal posture, the degree of rotation about each joint being weighted by a joint-specific expense factor.

Table 1 Planning to Reach a Target

Step 1	Given a starting posture and a target location, identify a candidate goal posture.
Step 2	Generate potentially more effective candidate goal postures (that come closer to optimizing all task constraints) until the planning deadline has expired.
Step 3	Evaluate moving directly to the goal posture. Check whether a direct movement to the goal posture would collide with any obstacle. If no potential collision is detected, continue with Step 4. If one *is* detected, perform steps 1' and 2', then continue to Step 4.
Step 1'	Given the starting posture and goal posture, identify a candidate via posture.
Step 2'	Generate potentially more effective candidate via postures, until the planning deadline has expired.
Step 4	Execute the direct or combined movement. Perform bookkeeping.

Step 3 is evaluating the movement trajectory so far identified and checking it for potential collisions. If Step 3 detects no potential collisions, the direct movement to the goal posture is immediately executed (in Step 4). Some "bookkeeping" is then performed, which consists of adding the newly generated posture to the store of known postures, forgetting the oldest stored posture if the posture store is filled, updating the planning deadline, and adjusting the planning parameters for subsequent actions, so they may be planned as efficiently as possible.

An example of planning a reach using a stick-figure representation of the actor is shown in Figure 1. The starting posture (Figure 1, Panel A) and other postures are represented in terms of the angular position of the hip, shoulder, elbow, and wrist joints. In this illustrative example, only the shoulder and elbow joints are free to move.

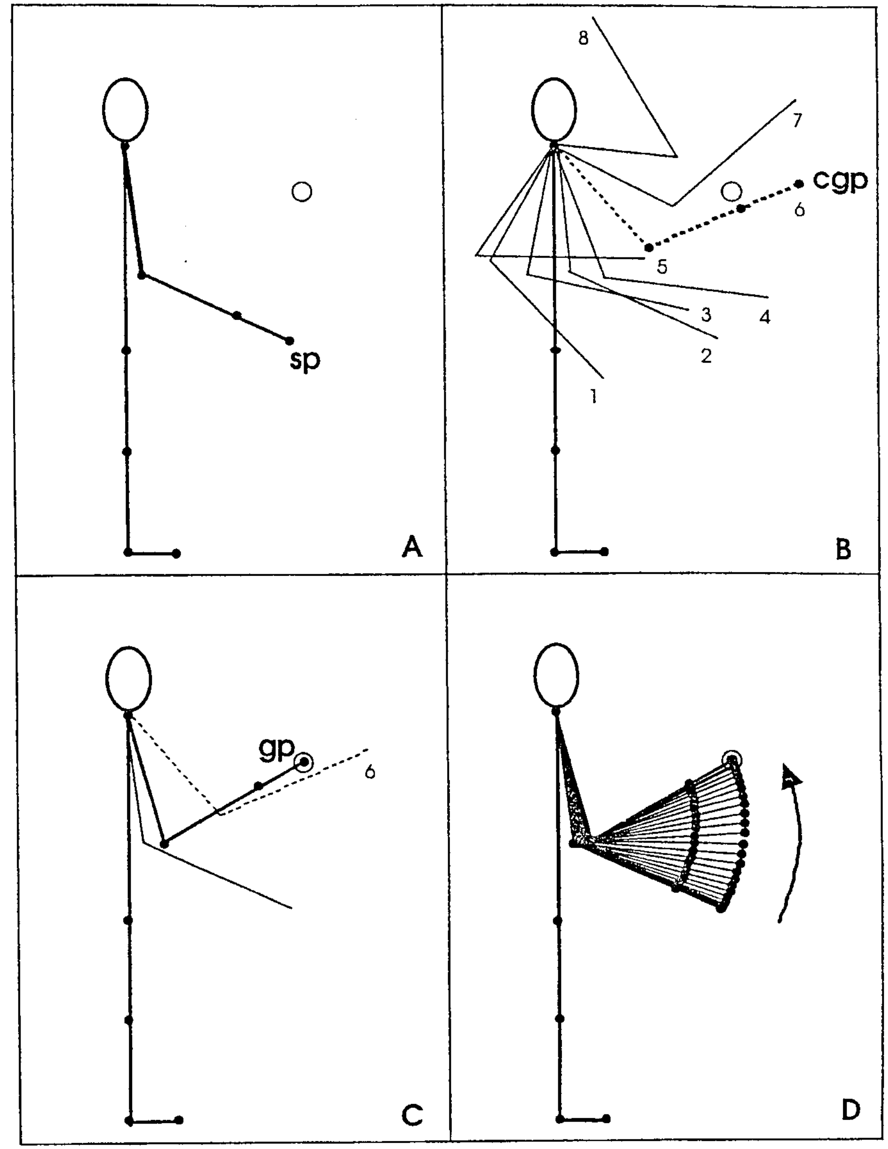

Figure 1 — Stick-figure representations of an actor planning a movement from a starting posture to touch a target (small circle). Panel A: starting posture (sp). Panel B: initial posture knowledge. For clarity a sample of 8 postures is shown, though the model used 30 stored postures. The most nearly adequate of the stored postures is identified as the candidate goal posture (cgp). Panel C: A more effective goal posture (gp) is generated based on variations of the candidate goal posture. Panel D: The movement is executed by transition through joint space from the starting posture to the goal posture.

The first planning step is to identify the provisionally best goal posture for moving to the target from among the currently stored postures. Panel B shows the initial posture knowledge of a "naïve" model whose only prior knowledge is eight postures distributed randomly in its workspace. For this reaching task, none of the stored postures reaches the target with acceptable accuracy, although one of them (stored posture 6) brings the end effector closest to the target, so it is identified as the provisional goal posture (see Table 1, Step 1). A more satisfactory goal posture can be found, however, as shown in Panel C of Figure 1. It is generated by variations bsed on the provisional goal posture (Table 1, Step 2).

Because there is no obstacle present in this particular task (Table 1, Step 3), the model makes the movement from the starting posture to the goal posture by straight-line interpolation through joint space, using a bell-shaped velocity profile as shown in Panel D of Figure 1 (Table 1, Step 4).

Via Posture and Trajectory Planning When There Is an Obstacle

The planning process just described will suffice as long as there is no obstacle between the starting posture and goal posture. However, when an obstacle is present, collision with the obstacle must be avoided. Obstacle avoidance is achieved in the model by means of a via movement superimposed on the previously planned direct movement to the goal. For each joint, the goal movement is a monotonic movement from the starting posture to the goal posture. The via movement is a transition from the starting posture to a hypothetical via posture followed by a return to the starting posture. Because the via movement adds no net displacement to the limb, when it is superimposed on the goal movement, the obstacle may be avoided, but the posture reached at the end (the goal posture) is the same as when no via movement is introduced.

What are the reasons for using this particular compound-movement strategy? Clearly the movement around an obstacle must change direction. An alternative model one might consider is to divide the direct movement from the starting posture to the goal posture into two successive movements—the first from the starting posture to a via posture, and the second from the via posture to the goal posture. If these two movements were individually planned, the resulting movement would be unrealistic: The limb would momentarily come to rest at the via point, and there would be an abrupt change in the direction of movement and/or a large change in acceleration at the via point. However, such momentary pauses and sudden changes of direction are not observed in everyday movements around obstacles (Dean & Brüwer, 1994; Sabes & Jordan, 1997). The composite movement proposed by the posture-based model achieves a more realistic, gradual change in direction during the obstacle-avoiding movement (cf. Nakano et al., 1999).

Figure 2 shows the rotations of a single joint (the elbow) in a hypothetical obstacle-avoidance movement. The top of the left panel shows the goal movement for the elbow, a rotation about the elbow joint of one radian from its starting angle to its goal angle. (Recall that the goal angle of a joint comprises one component of the entire goal posture, which is defined by the goal angles of all the joints of the body.) The direct movement from the start to the goal angle would cause a collision with an obstacle if an obstacle were present between the starting and target locations; this can be established on the basis of forward kinematics. A via movement must therefore be superimposed on the main movement to avoid the collision. The via movement (middle of the left panel of Figure 2) is a symmetric flexion–extension of the elbow. The via movement to and from the start position can be superimposed on the main movement, and the sum of these two movements (bottom of left panel of Figure 2) yields the same endpoint as would have been reached by the unmodified main movement. Hence, the position of the elbow at the end of the movement is the same when the obstacle is not avoided as when it is, but the trajectory to the goal posture is changed significantly by the addition of the via movement onto the main movement.

The right panel of Figure 2 shows the joint velocity function corresponding to the joint position function on the left of Figure 2. Note that the main movement's velocity curve is bell shaped. The via movement, by contrast, is biphasic. As a result, the composite movement is also biphasic.

To return to the planning process, once it is determined that movement from the starting posture directly to the goal posture would result in a collision (Table 1, Step 3), the model identifies a via posture. It does so by using essentially the same algorithm as the one used to identify the goal posture. The main difference is that the via posture is identified such that the combined movement executed in Step 4 will detour the obstacle. The just-identified goal posture (Figure 3, Panel A) will not be changed by the detour. Step 1' (Table 1) identifies a candidate via posture, the movement to and from which will be combined with the main movement to the

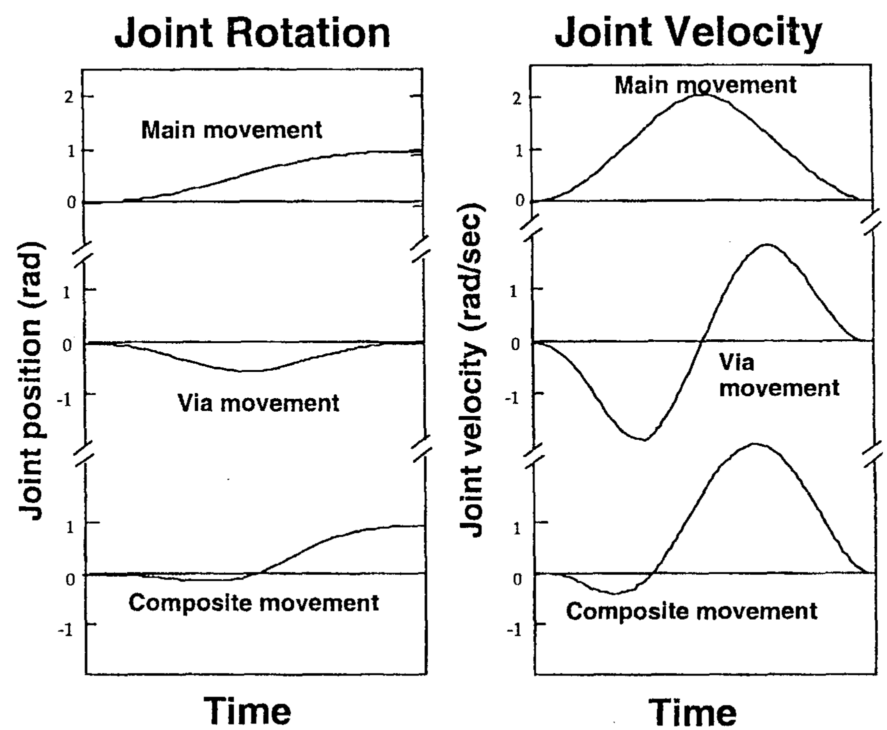

Figure 2 — Joint movements computed for obstacle avoidance. (Left Panel: One joint's rotation in avoiding an obstacle. Right Panel: The joint's velocity.)

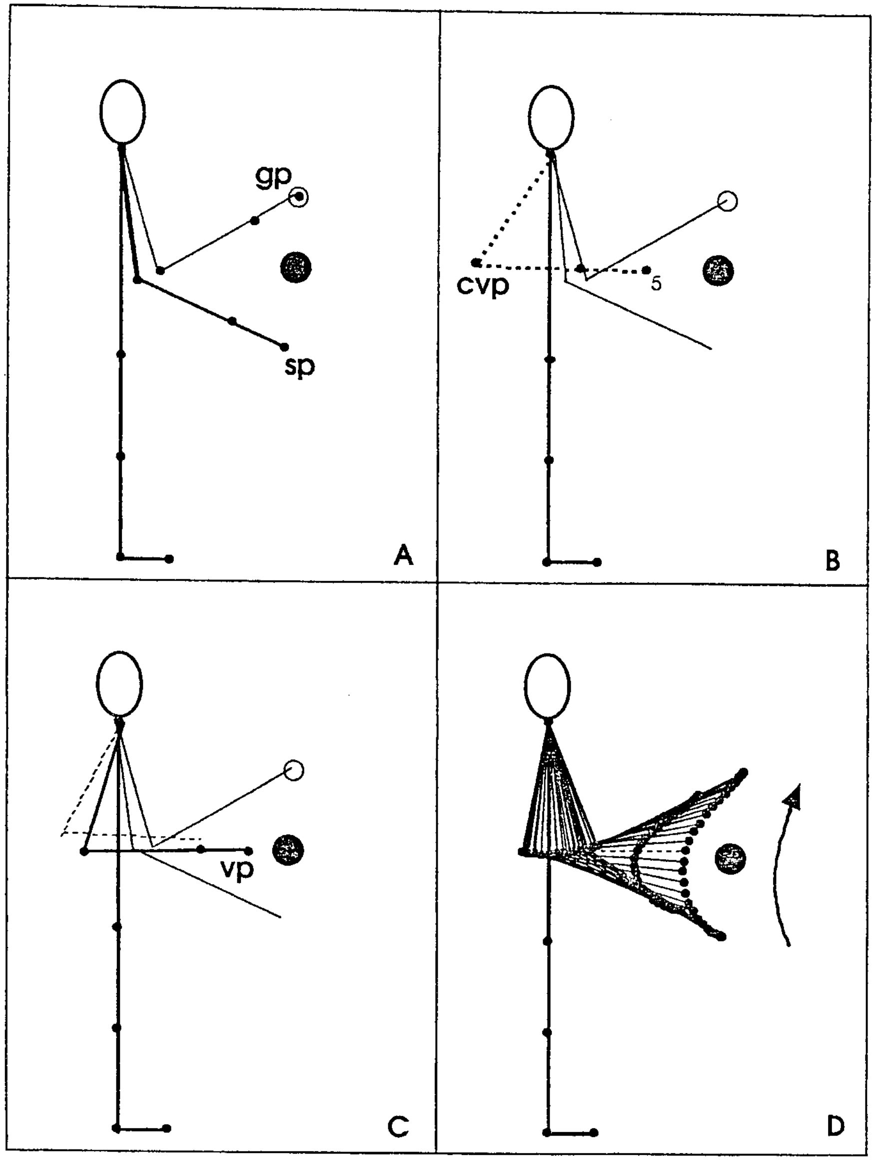

Figure 3 — Stick-figure representations of an actor planning a movement from a starting posture to touch a target (small circle) when an obstacle is present. Panel A: starting posture (sp) and previously identified goal posture (gp). Panel B: The most nearly adequate of the stored postures is identified as the candidate via posture (cvp). Panel C: A more effective via posture (vp) is generated based on the candidate goal posture. Panel D: The movement is executed by transition through joint space from the starting posture to the goal posture, using the combined main and via movements. The dotted line represents the via posture that was ultimately selected.

goal posture in order to avoid the collision (Figure 3, Panel B). In the example shown in Figure 3, the best stored posture is the fifth stored posture (as shown in Figure 1, Panel B). (For convenience of exposition, the via posture is represented in this figure as coinciding with the midpoint of the composite movement. However, since the via movement is reversible, it can be thought of as a relative movement between any two postures that would produce the necessary joint rotations.) Step 2' generates variations on the candidate via posture to identify a more effective candidate via posture (Figure 3, Panel C). Once the via movement has been identified, Step 4 executes the combined main and via movements (Figure 3, Panel D). Bookkeeping proceeds in the same manner as when no obstacle is present.

Evaluation of the Model

We tested the adequacy of the model in accounting for obstacle avoidance by using a simple task that required participants to move the hand repeatedly between two target locations, with or without an obstacle between them. To compare the model with actual performance, the repetitive reaching movements of 6 subjects were recorded, and the model was used to simulate their performance.

Method

Participants. Six right-handed Penn State University undergraduates (3 male, 3 female) served as subjects. Prior to data acquisition, infrared emitting diodes (IREDs) were attached with Velcro straps to each subject's right hip, right shoulder, right elbow, right wrist, and nail of the right middle finger. The IRED positions were recorded with an OPOTRAK motion recording system (Northern Digital, Waterloo, Ontario, Canada) at a sampling rate of 50 Hz. Unfortunately, the data from 1 subject (Subject 4) were not useable because the IRED positions were frequently occluded during the movements. This was discovered after the apparatus was disassembled, so the subject could not be replaced.

Apparatus. Each participant was instructed to stand at the edge of a metal bookcase (69 in. high by 48 in. wide) so that movement about the hip was constrained, but the shoulder and elbow were free to move over the back surface. In this manner, movements were constrained to a sagittal plane. While performing the task, the subject kept his or her head tilted to the right, so he or she could visually monitor the hand. Targets were metal jar lids, 2 in. in diameter, securely attached to the response surface. The top of the lids faced outward. The center of the top lid was 48.5 in. above the floor, and that of the bottom lid was 35 in. above the floor. Given these heights, the top target was located at the height of the typical subject's shoulder, and the bottom lid was located at the height of the typical subject's navel. The obstacle was a cylinder (an empty Planter's Cashew Nut container) 4 in. in diameter and 3 in. deep, which had a magnet attached to the inner side of its plastic lid. The centers of the targets were 11.75 in. from the subject's edge of the bookcase.

Procedure. Participants were instructed to move the hand back and forth between the two targets for 20 s in a self-paced manner, touching each target with the fleshy side of the most distal phalange of the right middle finger. Subjects were told that there was no need to begin as quickly as possible, that there was no need to move as quickly as possible, and that there was no need to stop as quickly as possible. They were simply to move back and forth in a relaxed manner, pausing briefly at each target, making sure the obstacle was never touched, and that at the end of each movement a target was touched firmly, but not hard, with the inner tip of the most distal phalange of the right middle finger. The obstacle-present and obstacle-absent conditions were each tested twice for each subject, once with the hand starting on the top target and once with the hand starting on the bottom target. The order in which the four combinations of starting position and obstacle presence or absence was balanced over subjects.

In each trial, the experimenter placed the obstacle either midway between the two targets (as precisely as possible on a circle drawn on the response surface) or at the same height but beyond the reach of the subject (as precisely as possible on another drawn circle). Once the cylinder was in its appropriate position, the experimenter told the subject to place the middle finger on the top or bottom target. He then started the OPTOTRAK recording and said, "Go." The OPTOTRAK continued recording for 20 s, after which a signal appeared on the computer monitor (seen only by the experimenter) indicating that the recording had ended, at which time the experimenter told the subject to stop. Before any experimental trials were run, the subject was asked to place the middle finger on the center of each target and on the center of the obstacle so the OPTOTRAK could be used to record these positions for calibration purposes. The entire session lasted 20 min.

Results

We examined the kinematics of the movements generated by the 5 usable subjects in both the obstacle-present and obstacle-absent conditions. To evaluate the model's account of the kinematics of movement, we first used the model to predict the subjects' observed trajectories in the obstacle-present conditions and then used the model to predict the subjects' observed trajectories in novel obstacle-present reaches and in obstacle-absent reaches. (We did not use the obstacle-absent reaches to independently estimate the joint expense factors. The reason for not doing so is that movement in the non-obstacle condition is relatively constrained; when there are only two joint degrees of freedom, the goal posture adopted is determined by the goal location, within the limits of required response accuracy. Thus, the joint expense factors would not affect the modeled goal posture very much in the non-obstacle condition. Nevertheless, as will be seen below, using the joint expense factors that were estimated from the obstacle-present data provided a good fit for those of the obstacle-absent condition as well).

In placing the fingertip at different locations in the sagittal plane, the participant has, in principle, four degrees of freedom: rotation about the hip, shoulder, elbow, and wrist. However, in this task, the participants were observed to make little use of the wrist in either the obstacle-present or obstacle-absent condition. Moreover, hip movements were effectively prevented by the subjects' leaning against the bookcase. Because the hip and wrist joints were not used, the model was given just two free parameters—an expense factor for the shoulder and an expense factor for the elbow. (The expense factors for the hip and wrist were set to an arbitrary value of 1.0.)

Parameter Estimation. To fit a single movement around an obstacle, one needs to identify the goal posture and via posture, given the starting posture, goal location, and location of the obstacle. It is easy to evaluate the fit of the modeled goal posture: Does it reach the goal location, and does it differ from the posture actually adopted by the subjects? However, there is not such a clear criterion for evaluating the via movement. The reasoning we adopted for evaluating the fit of the modeled via movement was as follows.

Recall that a via movement is a relative movement from one posture to another (the via posture) and return. The via movement is synchronized with the main movement: It starts when the actor first moves from the starting posture, and it is completed just as the main movement reaches the goal posture. The via movement's maximum contribution to the detour around the obstacle occurs, then, at the midpoint of the composite movement. For the purposes of modeling the via movement, then, the posture of the model at the midpoint of its movement was considered to be the via point so that it could be compared with the corresponding posture at the midpoint of the observed movement. So that this evaluation would not be distorted by variations in movement time, all movements were normalized to a movement time of 1 s.

To estimate the joint expense factors, we selected four non-consecutive movements (the 4th, 9th, 14th, and 19th) from each subject's first trial in the obstacle condition. (For one subject, who did not exactly follow the metronome on one movement, another movement was substituted.) The directions of the four modeled movements for each subject, then, were either down-up or up-down depending on the sequence of trials each subject experienced. For three subjects, the first trial began with a downward movement, and for the other two subjects, the first trial began with an upward movement. The model was given the starting posture of each movement, the target location (i.e., the eventual spatial location of the fingertip), and the center location and diameter of the circular obstacle. From these movements, we sought to predict the participant's goal posture and via posture, which together describe the modeled trajectory from the starting posture to the goal posture.

The shoulder and elbow expense factors were each varied between 0.05 and 1.0 in steps of 0.05 to find the expense factor values that minimized the sum of squared differences between the joint angles of the modeled and observed via postures and goal postures. The shoulder and elbow expense factors that best fit each subject's data are shown in columns 2 and 3 of Table 2. Across subjects, the best fitting elbow expense factor was consistently low (0.05 to 0.35) relative to the best fitting shoulder expense factor (0.10 to 0.40). With these expense factors, the model was able to closely reproduce the observed movement (Table 2, columns 4 and 5). The mean squared difference between the observed and mean shoulder and elbow angles ranged from 0.078 rad^2 (Subject 5) to 0.120 rad^2 (Subject 2). The proportion of variance in joint angles explained by the model averaged 0.914 across subjects.

Figure 4 shows representative observed (left) and modeled (right) movements from each of the five subjects (the first modeled movement for each subject). The model successfully plans a movement that avoids the obstacle in each case. However, the model does not entirely capture the symmetry of the subject's movements (see, for example, Subjects 3 and 5 in Figure 4), even though it identifies a via posture that adequately avoids the obstacle. The model was not constrained to move symmetrically or to maintain a minimum distance from the obstacle, so within the limits of the imposed planning deadline, the generated trajectory meets the constraints of avoiding the obstacle and moving efficiently.

Table 2 Fit of Model to Obstacle-Present Reaches

	Best-fitting expense factors		Fit to obstacle-present reaches		Fit to novel obstacle-present reaches		Fit to obstacle-absent reaches	
Subject	Shoulder	Elbow	D^2	R^2	D^2	R^2	D^2	R^2
1	0.10	0.05	0.0042	0.95	0.0101	0.86	0.0048	0.89
2	0.15	0.05	0.0039	0.97	0.0359	0.63	0.0101	0.85
3	0.20	0.10	0.0107	0.88	0.0097	0.88	0.0025	0.96
5	0.40	0.35	0.0067	0.91	0.0040	0.95	0.0088	0.87
6	0.15	0.05	0.0112	0.86	0.0215	0.64	0.0098	0.76
Mean	0.20	0.12	0.0073	0.914	0.0163	0.792	0.0072	0.866

Note. D^2 is the mean squared difference between observed and modeled shoulder and elbow joint angles of 30 postures that comprised each normalized reaching trajectory, rad². Each sample is based on four different reaches. R^2 is the proportion of total variance in joint angles explained by the model's fit to the observed data.

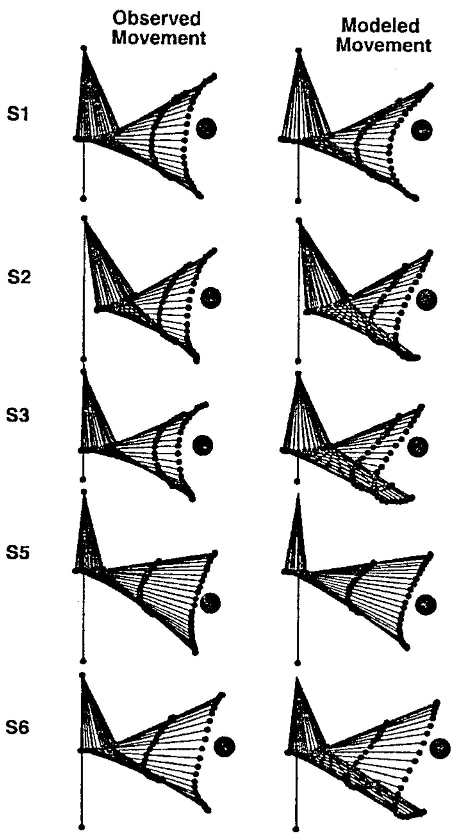

Figure 4 — Observed and modeled performance of five subjects' reaches around an obstacle. Left column: observed movements, normalized to a movement time of one second. Right panel: modeled movement. Heads and legs of stick-figures have been omitted for clarity.

Figure 5 provides an angle-angle plot of the four observed movements of the first participant (left panel), along with the plot (right panel) of the same four modeled movements. As seen here, the model captures the qualitative characteristics of the observed movements and does so with less movement-to-movement variability than in the observed movements.

Model Fit to Novel Data. Recall that each subject participated in two trials of repeated obstacle-avoiding movements and that the expense factors were estimated using reaches from the first trial only. To further evaluate the model, it was used to predict four movements at corresponding positions in the second obstacle-avoidance trial given only the starting posture and the target location and the expense factors previously identified. Columns 6 and 7 of Table 2 show the fit (D^2 and proportion of variance accounted for) when the model was applied to four reaches by the same subject from the other trial by that subject. On average, the model accounted for 0.79 of the variance in the joint angles of the previously unmodeled movements.

Model Fit When Obstacle Was Absent. To explore the generality of the obtained fit, we used the model to predict the movement between the starting and goal postures when no obstacle was present. We did this for four movements in the corre-

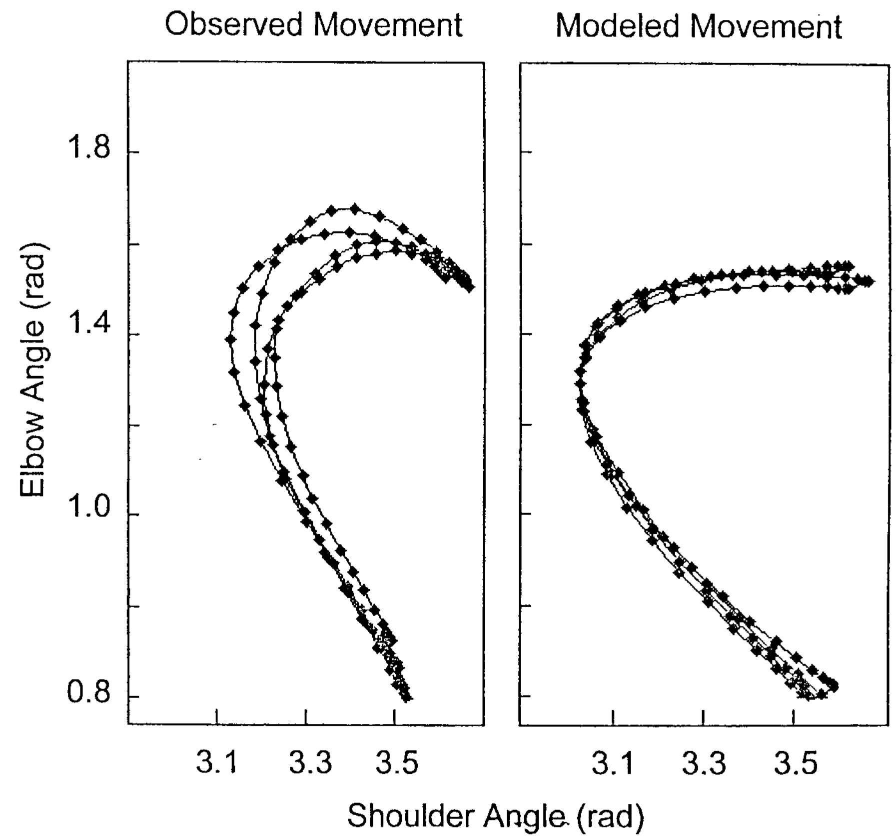

Figure 5 — Angle-Angle plots for shoulder and elbow joints during movements around an obstacle (four movements by Subject 1).

sponding positions of one of the two non-object movement trials. The results of this fit are shown in Figure 6, where it is seen that even though the joint expense factors was estimated from another task, the model captured the qualitative characteristics of the movements in the obstacle-absent condition. Columns 8 and 9 of Table 2 show the fit of the model for the obstacle-absent reaches. As seen here, on average the model accounted for 0.87 of the variance in the joint angles during the movement.

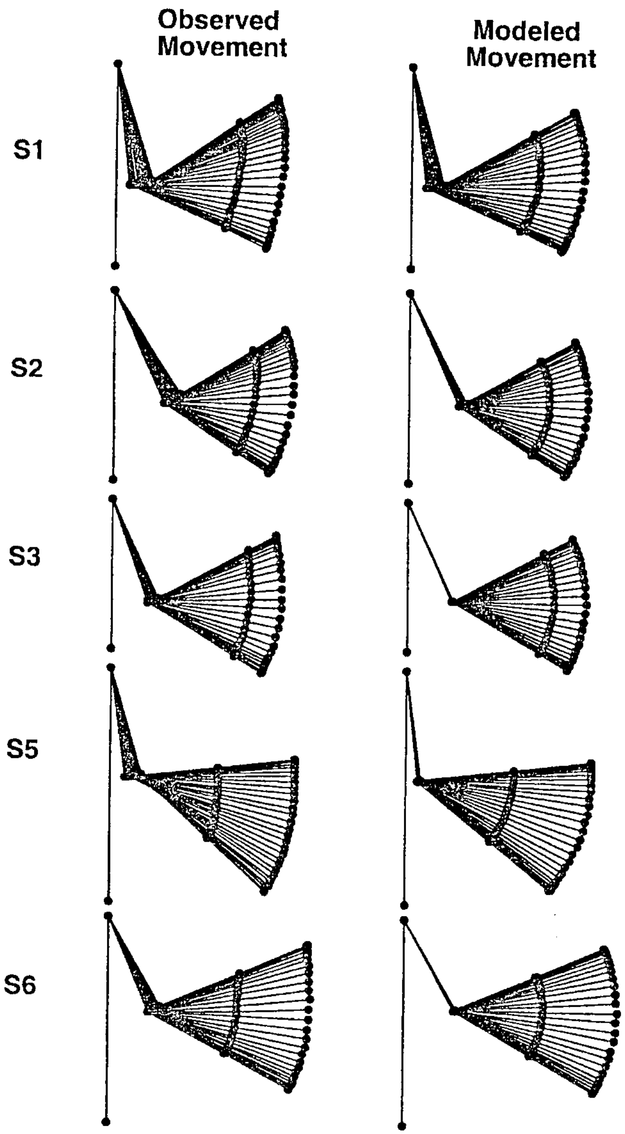

Figure 6 — Observed and modeled performance of five subjects' reaches when no obstacle is present. Left column: observed movements, normalized to a movement time of 1 s. Right panel: modeled movement. Heads and legs of stick-figures have been omitted for clarity.

Figure 7 shows the angle-angle plot for the shoulder and elbow for four movements of Subject 1 in the absence of an obstacle (left panel) and the corresponding plot for the model's performance (right panel). Because the model assumes that movements are made as straight lines through joint space with perfect synchronization between the joints, the model's angle-angle plots are linear, whereas the subjects' angle-angle plots show some curvature, indicating some decoupling of the joints' movements (Helsen, Elliot, Starkes, & Ricker, 2000). Staggering of joint motions has been ascribed to transfer of momentum between limb segments (Alexander, 1991), which is a kinetic feature that our model, so far purely kinematic, is not equipped to handle.

Sensitivity of the Model to Parameter Changes. Once a model's optimum parameters have been estimated, the question arises: How sensitive is the model to changes in the parameters? To explore this question, the model predicted the same four reaches for each of the 5 subjects, with the shoulder and elbow expense factors set to a constant intermediate value (0.15). The fit of the model (columns 2 and 3 of Table 3) with these non-optimal parameter values was markedly worse than with the optimal values: The proportion of explained variance in the joint angles dropped from 0.91 to 0.78.

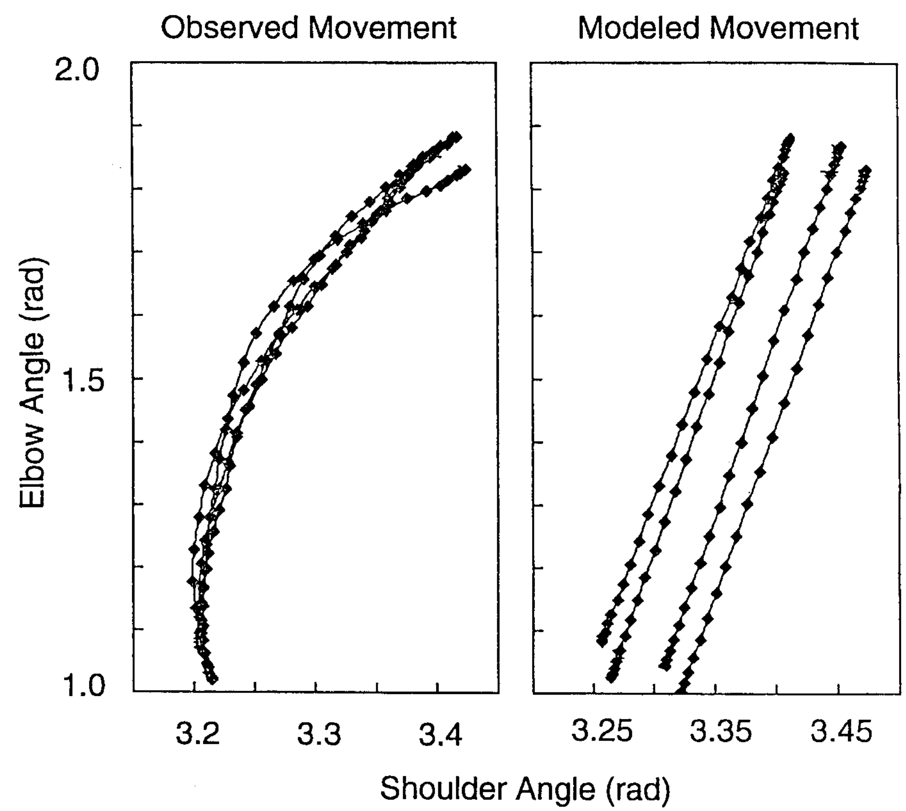

Figure 7 — Angle-Angle plots for shoulder and elbow joints during movements with no obstacle (four movements by Subject 1).

Table 3 Fit of Model to Same Subjects' Obstacle-Present and Obstacle Absent Reaches, and Fit Between Same Subjects' Observed Reaches

	Fit with equal expense factors (0.15, 0.15)		Fit between obstacle reaches in two trials	
Subject	D^2	R^2	D^2	R^2
1	0.0099	0.89	0.0100	0.88
2	0.0262	0.78	0.0346	0.71
3	0.0257	0.71	0.0021	0.98
5	0.0172	0.78	0.0029	0.96
6	0.0198	0.75	0.0152	0.81
Mean	0.0198	0.782	0.0130	0.868

Agreement Between Subjects. Finally, to provide a benchmark for the comparison of the model's agreement with the observed data, the variability from one subject to another was computed, using the same computational criteria as used for the comparisons between the model and each subject (columns 4 and 5 of Table 2). The mean squared difference across joints between four reaches by one subject and the corresponding reaches by another (Table 4) ranged from 0.01 to 0.08 rad^2. The mean of these values, 0.0360 rad^2, was markedly higher than that of the model's fit to the observed obstacle-avoiding reaches in Table 2 (mean = 0.0073 rad^2), the fit to novel obstacle-avoiding reaches (mean = 0.0163 rad^2), and the fit to non-obstacle reaches (mean = 0.0072 rad^2). The model, then, better fit the performance of each subject.

As seen above, the model was successful in accounting for the trajectories of reaches made in the presence and absence of obstacles. The squared difference measures of the fit to the data were on average better for the obstacle reaches to which the model was fit (D^2 = 0.0073) than to the other obstacle reaches by the same subject (D^2 = 0.0163). Nevertheless, for subjects 3 and 5, the fit to the non-modeled reaches was actually better. For all reaches, the mean fit (D^2 = 0.0118) was as good as the within-subjects "fit" between a reach in one trial and the corresponding reach in another trial (mean D^2 = 0.0130). For all intents and purposes, then, the model was an effective proxy for a human subject, using within-subject and subject-to-subject variability as criteria.

Clinical Implications

As has often been observed, there is nothing so practical as a good theory. As of yet, however, the practical implications of the posture-based model are not fully clear. Nevertheless, a fruitful avenue for applied research is to determine how various disorders affect performance, and then to see if those deficits can be related to specific aspects of the model. Let us look, then, at how each stage of the model might correspond to specific clinical deficits in movement.

Table 4 Fit Between Pairs of Subjects (A and B) in the Obstacle–Present Condition

	Subject B			
Subject A	2	3	5	6
1	0.0795	0.0191	0.0306	0.0402
2		0.0276	0.0687	0.0179
3			0.0305	0.0098
5				0.0360
Mean	0.0360			

Definition of Task Constraints

The model first defines a task by establishing relevant constraints such as identifying a target for movement. At the highest level, attentional and planning mechanisms are required if attention is to be directed to a part of the work area, and if movement towards that area is to be initiated, or if obstacles in that area are to be avoided. It is well known that disruptions of certain brain regions (e.g., right parietal ischemia) can affect attention to part of the workspace, as revealed in the clinical symptoms of hemi-inattention and extinction. While they are not directly connected to motor control, these clinical symptoms are often accompanied by hemiparesis. Similarly, left-hemisphere injuries that produce aphasia are commonly accompanied by hemiparesis (especially Broca's aphasia, and aphasias resulting from mixed extrasylvian, supplemental motor area, global, or subcortical injuries; Heilman & Valenstein, 1993). Patients presenting with right-hemisphere injury that causes neglect make movements to the neglected side with considerably more curvature than control participants, especially when the movements are visually guided (Jackson, Newport, Husain, Harvey, & Hindle, 2000). Because the visually guided movements are particularly affected, the deficit is presumably more closely associated with localization of the target of the movement (i.e., definition of the constraints defining the task) than with motor planning per se. Finally, still in the task-definition stage, deficits have been observed in what we might describe as the "long-range" planning of patients with unilateral brain damage. When clinically normal individuals decide how to grasp an object, they typically take into account the position they must eventually adopt to complete the task—the so-called end-state comfort effect (Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993). Patients with right-hemisphere brain damage, however, tend to adopt stereotyped grips (typically, "overhand" grips) of a rod in order to manipulate it, with the result that completion of the manipulation often results in the need for the adoption of awkward postures at the end of the movement (Hermsdörfer, Laimbruber, Kerkhoff, Mai, & Goldenberg, 1999; Steenbergen et al., 2000). Because the model assigns priority to the specification of end-states, it is generally consistent with the model that end-state planning is particularly disrupted in a clinical group.

This outcome encourages the alignment of a stage of planning in the model with a brain circuit that can be selectively damaged, leading to a well-defined behavioral deficit.

The Specific Steps of Planning

Each of the planning steps of the model may suggest ways that injury might impair performance. In Step 1 of planning to reach a target, and in Step 1' of planning to avoid an obstacle, a candidate goal posture or via posture is selected from the stored postures that have been previously learned (see Table 1). Next, the model (normally) generates variations in order to find a better (more adequate or more efficient) posture by searching for alternatives beginning from the provisional posture (Step 2 or Step 2'). One possible locus of planning failure that would lead to impaired motor performance would be failure to execute one of these steps—due, for example, to inadequate representation of one side of the body. While the consequences of such failure might resemble some motor disorders such as generalized apraxia, a global failure to execute one of the steps would impair performance bilaterally and so could not explain spastic hemiparesis.

Step 4 of the model specifies a mechanism for the control of movement, vis-à-vis the generation of movement trajectories that follow a bell-shaped velocity profile in joint space (see Rosenbaum et al., 2001, for more details). Some motor deficits, such as Parkinsonism, are characterized by disruptions of both the initiation of movements and fine control of movement trajectories (e.g., Glencross & Tsouvallas, 1984; Wing, Keele, & Margolin, 1984). In particular, Parkinsonism often produces micrographia and bradykinesia as well as difficulties in initiating voluntary movements. The other constructs of the model—the computation of forward kinematics (Steps 2 and 2'), and the ability to "try out" potential movement trajectories to test for collisions (Step 3)—suggest other plausible locales for potential motor dysfunction. In particular, the computations of eventual effector positions from postures (Steps 1 and 2, and Steps 1' and 2') depend, presumably, on separate representations of postures for each side of the body, given that limbs on each side are controlled by the contralateral hemisphere. A deficit in posture storage on one side could produce inaccurate movements (due to inadequate relation of intended postures to effector locations) or collisions due to inadequate evaluation of intended movement trajectories. Inaccurate movements are, of course, observed in spasticity. For example, Steenbergen, Veringa, De Haan, and Hulstijn (1998) observed impaired typing function in cerebral palsy; performance using the unimpaired hand was much better.

Difficulty in motor control may sometimes appear in the final motor control path. For example, in spastic hemiparesis arising from ischemic cerebral lesions, Fellows, Kaus, and Thilmann (1994) reported impaired movement accuracy attributable to agonist muscle paresis rather than antagonist muscle resistance. Such a deficit would correspond in our model to imprecision in the programming or execution of movement trajectories. We may speculate that some or all of the prefrontal cortex, supplemental motor areas, and basal ganglia may be involved by analogy to the anatomical areas that are reportedly involved in Parkinsonian symptoms (Heilman & Valenstein, 1993).

To summarize, the structure of the model suggests four general ways that motor planning might be impaired: (a) failure in specifying (or recognizing the importance of) all of the constraints that define a task; (b) inaccuracy in the storage of postures once generated; (c) inaccuracy in the computation of the limb positions by forward kinematics; and (d) noise in the eventual execution of motor movements. We can speculate that in spastic hemiparesis, which is markedly lateralized,

motor execution noise might be the most plausible of these assumptions, but further research will be required to resolve the question. Meulenbroek, Rosenbaum, and Vaughan (2001) address the simulation of reduced movement capabilities in greater detail.

When all is said and done, human movement is remarkably adaptive. Both acute and chronic impairments of movement are usually compensated for. The case of spastic hemiperesis offers an unusual insight into how the planning process may contribute to this compensation. As noted above, the model of movement planning begins with the assumption that every task is defined by a set of constraints. Some of these constraints are external, and defined by the task (reach here, tap there, etc.), but others are internal (the range of joint movement, or limitations imposed by disease or injury). In the case of spastic hemiperesis, the full range of motion of one limb is limited, and reaching movements with the impaired hand are accompanied by compensatory movements of the trunk that are larger than those observed in reaching with the unimpaired hand (Steenbergen, Thiel, Hulstijn, & Meulenbroek, 2000). In the model's terms, in spastic hemiparesis, nature has imposed an arbitrarily high expense factor on shoulder and elbow joint movements so that goal postures involving more trunk movement must be selected to accomplish reaching tasks than when the unimpaired hand moves alone. This is accomplished by setting the expense factor for the impaired joint to an arbitrarily high value.

In bimanual movements of participants with spastic hemiparesis, the unimpaired limb adopts the time scale of the impaired limb, and more trunk movement is involved (Steenbergen et al., 2000; Van Thiel & Steenbergen, 2001). Qualitatively (again in the model's terms) in bimanual movements, planning appears to impose similar constraints (joint expense factors and speed of movement) on both limbs, so the range of trunk movement is greater and the speed of movement slower in the unimpaired limb as well as in the impaired limb. Interestingly, joint-joint angle plots reveal that in the unimpaired limb, movements are more closely coordinated across joints, which suggests that the constraints on movement (e.g. straight-line movement through joint space) are not compromised by the unimpaired limb's participation in the bimanual movement.

In summary, the posture-based model has demonstrated the capability of reaching in a realistic fashion, reaching around an obstacle, and compensating for injury or immobilization of a joint. The model also provides an effective theoretical framework for further studies of normal and impaired movement and for its extension to the understanding of more complex movements such as grasping objects (Meulenbroek et al., 2001).

References

Alexander, R.M. (1991). Optimum timing of muscle activation for simple models of throwing. *Journal of Theoretical Biology*, **150**, 349-372.

Bernstein, N. (1967). *The coordination and regulation of movements*. London: Pergamon.

Dean, J., & Brüwer, M. (1994). Control of human arm movements in two dimensions: Paths and joint control in avoiding simple linear obstacles. *Experimental Brain Research*, **97**, 497-514.

Fellows, S.J., Kaus, C., & Thilmann, A.F. (1994) Voluntary movement at the elbow in spastic hemiparesis. *Annals of Neurology*, **36**, 397-407.

Glencross, D., & Tsouvallas, M. (1984). Processing of proprioceptive information in Parkinson's disease patients. *Australian Journal of Psychology,* **36**, 343-354.

Heilman, K.M., & Valenstein, E. (1993). *Clinical neuropsychology* (3rd ed.). New York: Oxford University Press.

Helsen, W.F., Elliott, D., Starkes, J., & Ricker, K.L. (2000). Coupling of eye, finger, elbow, and shoulder movements during manual aiming. *Journal of Motor Behavior,* **32**, 241-248.

Hermsdörfer, J., Laimbruber, K., Kerkhoff, G., Mai, N., & Goldenberg, G. (1999). Effects of unilateral brain damage on grip selection, coordination, and kinematics of ipsilesional prehension. *Experimental Brain Research,* **128**, 41-51.

Jackson, S.R., Newport, R., Musain, M., Harvey, M., & Hindle, J.V. (2000). Reaching movements may reveal the distorted topography of spatial representations after neglect. *Neuropsychologia,* **38**, 500-507.

Logan, G.D. (1988). Toward an instance theory of automatization. *Psychological Review,* **95**, 492-527.

Meulenbroek, R.G.J, Rosenbaum, D.A., & Vaughan, J. (2001). Planning reaching and grasping movements: Simulating reduced movement capabilities in spastic hemiparesis. *Motor Control.*

Nakano, E., Imamizu, H., Osu, R., Uno, Y., Gomi, H., Yoshioka, T., & Kawato, M. (1999). Quantitative examinations of internal representations for arm trajectory planning: Minimum commanded torque change model. *Journal of Neurophysiology,* **81**, 2140-2155.

Rosenbaum, D.A., Meulenbroek, R.G.J., Vaughan, J., & Jansen, C. (in press). Posture-based motion planning: Applications to grasping. *Psychological Review.*

Rosenbaum, D.A., Meulenbroek, R.G.J, & Vaughan, J. (2001). Planning reaching and grasping movements: Theoretical premises and practical implications. *Motor Control.*

Rosenbaum, D.A., Vaughan, J., Jorgensen, M.J., Barnes, H.J., & Stewart, E. (1993). Plans for object manipulation. In D.E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV—A silver jubilee: Synergies in experimental psychology, artificial intelligence and cognitive neuroscience* (pp. 803-820). Cambridge, MA: MIT Press.

Sabes, P.N., & Jordan, M.I. (1997). Obstacle avoidance and a perturbation sensitivity model for motor planning. *The Journal of Neuroscience,* **15**, 7119-7128.

Steenbergen, B., Hulstijn, W., & Dortmans, S. (2000). Constraints on grip selection in cerebral palsy: Minimising discomfort. *Experimental Brain Research,* **134**, 385-397.

Steenbergen, B., van Thiel, E., Julstijn, W., & Meulenbroek, R.G.J. (2000). The coordination of reaching and grasping in spastic hemiparesis. *Human Movement Science,* **19**, 75-105.

Steenbergen, B., Veringa, A., De Haan, A., & Hulstijn, W. (1998). Manual dexterity and keyboard use in spastic hemiparesis: A comparison between the impaired hand and the "good" hand on a number of performance measures. *Clinical Rehabilitation,* **12**, 64-72.

Van Thiel, E., & Steenbergen, B. (2001). Trunk-assisted arm movements in hemiparetic cerebral palsy. *Motor Control.*

Wing, A.M., Keele, S., & Margolin, D.I. (1984). Motor disorder and the timing of repetitive movements. *Annals of the New York Academy of Sciences,* **423**, 183-192.

Acknowledgments

This article is based on a talk presented at the *International Workshop on Studies and Models of Human Prehension: Contributions to Understanding Grasping Pathology.* Werkenrode, Groesbeek, The Netherlands, January 13, 2000. The authors are grateful for support from the Hamilton College Faculty Research Fund, the Ralph E. Hansmann Science Student Support Fund, grants BNS-90-08665 and SBR-94-96290 from the National Science Foundation, Research Scientist Development Award K02-MH00977 from the National Institutes of Health, the Royal Netherlands Academy of Arts and Sciences, and the Dutch Organization for Scientific Research (NWO Stimulans Premie). We thank two anonymous reviewers, Bert Steenbergen, and Wouter Hulstijn for their helpful comments on drafts of the manuscript. Finally, we appreciate the assistance of our students Tiffany Mattson, Clara McAuley, Emma Thompson, and Rebecca Wadler (all of Hamilton College), and Jeremy Graham (Pennsylvania State University).