

**THE POSTURE-BASED MOTION PLANNING FRAMEWORK:
NEW FINDINGS RELATED TO OBJECT MANIPULATION, MOVING AROUND
OBSTACLES, MOVING IN THREE SPATIAL DIMENSIONS,
AND HAPTIC TRACKING***

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ABSTRACT

We describe the results of recent studies inspired by the posture-based motion planning theory (Rosenbaum et al., 2001). The research concerns analyses of human object manipulation, obstacle avoidance, three-dimensional movement generation, and haptic tracking, the findings of which are discussed in relation to whether they support or fail to support the premises of the theory. Each of the aforementioned topics potentially challenges the theory's claim that, in motion, goal postures are planned before the selection of movements towards those postures. However, even the quasi-continuous phenomena under study show features that comply with prospective, end-state-based motion planning. We conclude that progress in motor control should not be frustrated by the view that no model is, or will ever be, optimal. Instead, it should find promise in the steady growth of insights afforded by challenges to existing theories.

1. INTRODUCTION

One measure of progress in a field is the complexity of the phenomena it can account for. The field of motor control is no exception. As progress has been made in motor control, researchers have sought to describe more and more complex phenomena at a level of detail previously reserved for only the simplest kinds of phenomena. Thus, in years past it was sufficient to describe the kinematics of a single point at the end of the limb segment chain – for example, the wrist of a person’s arm as the hand moved from location to location on a horizontal surface. As the field has matured, however, investigators have grown hungrier. They have sought to describe the entire body in motion, characterizing, for example, all the joint angles of an individual moving from place to place in three spatial dimensions, reaching for objects, avoiding other objects, and using feedback of various kinds – visual, auditory, and haptic – to guide subsequent behavior. Even this set of aims is small compared to what ultimately needs to be accounted for – understanding the control of forces, appreciating how individuals work with others, recognizing how movements interlace with motivations, and so on – but fully characterizing basic movement forms is still a tall order. It would be a significant step forward to predict the series of body positions adopted by an individual of known size, shape, and disposition, when he or she carries out some task such as grasping an object and moving it to some other place in the environment.

In this chapter we provide a brief review of the lines of work that have arisen from our desire to provide such an account. The aims of our work are intimated in the foregoing paragraph. We have focused on manual control, especially for tasks such as reaching for objects and reaching around obstacles. The model we have developed is for planar reaching movements, as described in section 2 below, but we have also used the model as a springboard for asking new questions about object manipulation (section 3), obstacle avoidance (section 4), moving in three spatial dimensions (section 5), and using feedback, especially haptic feedback, to guide movement and eliminate the need for detailed planning (section 6).

Some caveats are in order. First, we have restricted our attention to kinematics (the description of positions without regard to forces), leaving kinetics (the description of positions with regard to forces) for another day. Second, the individuals whose performance we have studied comprise a small fraction of the populations who engage in motor control. We have focused on movements made by healthy young adults (mostly college students) and individuals with a small subset of the neurological disorders that afflict people. Babies, young children, the elderly, other patient groups, animals, and robots have so far been beyond our ken. Third, the scientific subculture in which we work is inhabited by cognitive psychologists (those who pursue the scientific study of mental function). For the most part, these individuals have viewed motor control as the province of neurophysiology and engineering, and thus have not seen it an obviously interesting area of study for the analysis of mental functioning (see Rosenbaum, 2005). We have tried to show that motor control is in fact one of the most fundamental areas for tapping into the computational basis of skill. In so doing, we have also tried to reach neurophysiologists and engineers who may

have not fully appreciated what psychology has to offer the study of motor control.

2. THE POSTURE-BASED MOTION PLANNING THEORY

For the past several years, we have been working on a cognitive psychological model of motor control, designed as much to address fundamental issues of planning and decision-making as to address the “nuts and bolts” of neuro-muscular control itself. Understanding how plans are formed and how decisions are made is a fundamental challenge for cognitive psychology. Plans and decisions typically involve complex forms of action, so understanding how plans are formed and decisions are made for relatively simple motor acts can inform the understanding of large-scale planning and decision making.

An important insight into the nature of planning and decision-making is that neither process relies as heavily on optimizing as was once believed. Herbert Simon, a Nobel Prize winner in Economics, showed that decision-making usually involves satisfying rather than optimizing values. Thus, managers usually strive to get costs below some threshold and get profits above some other threshold, rather than minimizing costs and maximizing profits per se. A further insight was provided by Tversky (1972), who showed that decision-making is efficient when decision-makers winnow now rather than optimize. Winnowing involves pruning: Candidate solutions that fail to satisfy the most important constraint are winnowed first, candidate solutions that fail to satisfy the second most important constraint are winnowed second, and so on. If more than one candidate solution satisfies the least important constraint, the choice between or among those candidates is made at random.

Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) applied Simon’s and Tversky’s insights to motor control. They argued that decision-making about movement is formally no different from other kinds of decision-making, such as which car to buy or which person to hire. As in shopping or hiring, the individual deciding on a course of physical action faces a wide range of options, akin to Bernstein’s (1967) degrees of freedom problem. Choosing a particular physical action, Rosenbaum et al. (2001) argued, might best be understood as a winnowing process. In making this suggestion, these authors rejected optimization, recognizing instead that optimization was, and continues to be, the prevailing approach to motor control (Todorov, 2004).

Winnowing implies a ranking of constraints from most to least important. Where do these constraints come from, and who or what ranks them? The answer given by Rosenbaum et al. (2001) is that the actor, in response to the environment, implicitly ranks the constraints to be satisfied. In so doing, s/he defines the task to be performed. Thus, the internal representation of a task is a ranking of constraints, or what Rosenbaum et al. (2001) called a *constraint hierarchy*.

In our 2001 paper, we suggested that the constraints relevant to reaching and grasping pertain to features of body positions that can be adopted during forthcoming movements and also, more importantly, the *goal postures* that can be adopted when movements terminate (Figure 1). The latter suggestion was supported by results concerning the superiority of memory for positions

over movements (Smyth, 1984), results concerning the achievement of equifinality in studies related to the equilibrium point hypothesis (Bizzi et al, 1992; Graziano, Taylor, & Moore, 2002), and the fact that position variability decreases rather than increases as target positions are approached (Newell & Corcos, 1993). In the paper by Rosenbaum et al. (2001), it was hypothesized that goal postures are planned before movements are planned, though if the resulting planned movements are too costly, the goal postures may be reconsidered (cf. Kawato, 1996).

According to the theory, the way an actor plans goal postures is to evaluate recently adopted, stored goal postures with respect to the current constraint hierarchy. If time permits, whichever stored goal posture is the best candidate for the task at hand is “tweaked” so a possibly better goal posture may be found. The tweaking process, whose detailed computational features are presented in Rosenbaum et al. (2001), makes it possible to generate new goal postures.

Once a goal posture is selected, a movement to the goal posture is formed. This process likewise relies on a constraint hierarchy. In the model, ideal movements are assumed to have bell-shaped velocity profiles (Hogan, 1984). If internal simulation of the planned movement suggests that a collision will occur, the planned movement is reshaped by superimposing another movement on it. The superimposed movement is made from the starting posture to a planned “bounce posture” and then back to the starting posture. The bounce posture is chosen in the same manner as a goal posture except for the constraint hierarchy that is used (i.e., one that yields an adaptive composite movement). If a movement is made from the starting posture to the bounce posture and back while the main movement is made from the starting posture to the goal posture, the combined movement can have a shape that depends on the start posture, bounce posture, and goal posture.

In this brief review we cannot summarize all the reasons for the assumptions underlying the model, all the computations it uses, why the model was modified from earlier ones (Rosenbaum et al., 1991, 1993, 1995), what range of phenomena it can explain, or what new phenomena it predicts. For reviews, see Rosenbaum and Dawson (2004), Jax et al. (2004), and Rosenbaum et al. (2001). Suffice it to say the model has sufficient predictive power to motivate its continued pursuit, as outlined in the remainder of this chapter.

3. OBJECT MANIPULATION

As indicated above, we have pursued the model in the domain of object manipulation. The main reason for going in this direction, aside from the fact that grasping and moving objects is important in everyday life, is that the way objects are manipulated can reflect the nature of the plans regarding their future use. In other words, the way objects are grasped can depend on what will be done with them, and those changes in grasps can in turn reveal what information is available to, and considered by, the actor about what s/he will do later.

An early observation that hinted at the promise of this approach concerned a waiter filling glasses with water (Rosenbaum et al., 1990). The glasses were inverted and the waiter took hold

of each one with an awkward thumb-down grasp. Why he did so was quickly apparent. Taking hold of the glass with a thumb-down posture made it possible, after the glass was turned upright, for the waiter's hand to occupy a less awkward, thumb-up grasp when the glass was being filled. This observation suggested that the waiter was implicitly aware of his later postures. Subsequent experiments confirmed the reliability of this *end-state comfort* effect (Rosenbaum et al, 1990).

More recently, Cohen and Rosenbaum (2004) showed that an analogous anticipatory effect holds for *where* people take hold of objects, not just *how* they do so (with an overhand or underhand grip). As shown in Figure 2, participants in this experiment were asked to reach out and take hold of a common object (a bathroom plunger) to carry it from its initial position (on a platform of fixed height) to one of a number of target platforms of varying height. As shown in Figure 3, participants grasped the plunger at different heights depending on where they would bring it next: The higher the target platform, the lower the grasp height. This outcome, like the choice of overhand or underhand grips, reflected sensitivity to future task demands. By varying grasp heights, participants ended their object transports near the middle of the range of motion of the joints. This outcome indicates that participants planned their goal postures well in advance of initiating the movements they made to those goal postures, as in the earlier studies of the end-state comfort effect and consistent with the claims of the posture-based motion planning model. Other object manipulation studies led to the same conclusion (for review, see Rosenbaum et al, 2006).

Results such as these support the hypothesis that goal postures are planned before movements are initiated. This support in turn lends credence to simulations of object manipulation based on the posture-based motion planning model. As described in Rosenbaum et al. (2001) and Meulenbroek et al. (2001), many results concerning the kinematics of reaching and grasping, originating with classic observations by Jeannerod (1984) and others (see MacKenzie and Iberall, 1994, for review) can be simulated with the model. The simulation results concern such factors as the relation between maximum grip aperture and object width, the time of maximum grip aperture relative to arm movement, and so on.

4. OBSTACLE AVOIDANCE

Reaching for objects entails obstacle *avoidance* as well as object *attainment*. Indeed, the need to avoid obstacles arises more often than one might first assume. One's own body can be an obstacle. Thus, touching one's left ear with one's right index finger requires movement of one's right hand around one's head. Thus, obstacles can exist even when they are unseen and intrinsic. However, even when an object is reached and no obstacle is in the way, the object itself can be a kind of obstacle if it is approached incorrectly. For example, reaching for a cup will result in a collision if the fingers are too close to the cup as the hand approaches it or if the cup is approached from the wrong angle.

As mentioned above, we have simulated obstacle avoidance by allowing for predictions of

possible collisions and reshaping of planned movements when such collisions are anticipated. Also as indicated above, the reshaping of movements is achieved by superimposing onto the main movement from the starting to the goal posture a movement that goes from the starting posture to a bounce posture and back.

Two aspects of our work have allowed us to further explore these ideas concerning obstacle avoidance. One is simulation of this form of behavior (see Rosenbaum et al., 2001, and Vaughan et al., 2001). A technical detail about these simulations is that the movement from a starting posture to a bounce posture and back is done on a joint-by-joint basis with all the moving joints beginning and ending their trips together, coincident with the main movement from the starting posture to the goal posture. The angular velocity for any given joint moving in normalized movement time, $0 \leq t \leq \pi$, is given by $v(t) = \sin(t) \times \sin(t)$ for the main movement and by $v(t) = \sin(t) \times \sin(2t)$ for the back-and-forth movement. The function for the main movement provides a close approximation to a minimum-jerk movement in joint space (Hogan, 1984; Klein-Breteler & Meulenbroek, 2006). When the equations for the main movement and back-and-forth movement are used to generate theoretical reaches around obstacles, the modeled reaches closely approximate those observed in actual obstacle circumvention (Vaughan et al., 2001).

The second aspect of our work that relates to obstacle avoidance pertains to new behavioral studies we have done on sequential effects. Studies by Jax and Rosenbaum (2007) showed that people tend to make unnecessarily curved movements toward targets when obstacles are remembered but do not in fact appear. Based on this finding, we went on to ask how a series of manual positioning movements might depend on previous obstacle-avoidance movements when there was no question about the presence or absence of obstacles. In the newer studies (van der Wel, Jax, Fleckenstein, & Rosenbaum, in press), we asked participants to tap with the base of a hand-held, vertically oriented cylinder on each of a series of targets arrayed in a flat semi-circle. Each tap was to be made in time with a metronome. In the control conditions, no obstacle stood between any targets, but in the experimental conditions an obstacle stood between any given pair of targets. The participant was supposed to tap successive targets in time with the metronome, and if an obstacle stood in the way, to manually hurdle over the object in time with the beat. The required tapping rate was low enough that subjects could successfully coordinate their taps with the metronome, even when an obstacle stood between the targets. The result of primary interest was that after the obstacle was cleared and successive movements were made between targets, the hand moved higher than it did when no obstacle had just been cleared. This tendency to generate higher-than-normal arcs persisted for several subsequent target-to-target movements, although, like a bouncing ball, the peak heights decreased with successive jumps. These results indicate that the sequential effects observed by Jax and Rosenbaum (2007) did not depend on subjects' being unsure about obstacle appearance. More generally, the results of Jax and Rosenbaum (2007) and van der Wel et al. (in press) show that there are marked sequential effects related to obstacle avoidance. Existing models of manual control, including the posture-based motion planning model, do not predict these effects.

5. MOVING IN THREE SPATIAL DIMENSIONS

The posture-based motion planning model as described above was limited to postures occupying a plane. In such a 2-D model, each joint's movement can be represented as a series of joint angles between a start joint angle and a final joint angle, with the series of joint angles following some angular velocity profile such as a minimum-jerk curve. Different joints' motions may start or stop their angular excursions synchronously or asynchronously.

A more ambitious model of motor performance aspires to describe and predict performance in the more realistic situation of moving in 3-D. Extending the model to 3D turns out to be more challenging than might be expected.

The main challenge is related to the fact that joints moving in 3-D can have more than one possible axis of rotation. For example, the upper arm can be flexed, abducted, and rotated, and the forearm can be both flexed and pronated. Thus, the range of postures that can be adopted is greater in 3-D than in 2-D, and the attitude of each joint cannot be represented by a single angle of rotation. Furthermore, in 3-D, successive rotations do not commute (Gielen et al., 1997). That is, the order of rotations affects the end posture, which is not true in 2-D.

To address these challenges, we pursued a generalization of the 2-D model to 3-D by adopting a posture representation in which the rotation of each joint during the transition from one posture to another is represented as a single rotation about a variable axis of rotation – a so-called *quaternion* representation (Altman, 1986). With this approach, planning can be accomplished using the same general principles as in the 2-D case (Vaughan, Rosenbaum, & Meulenbroek, 2006).

A representative outcome (Figure 4) is a simulation of an obstacle-avoiding movement made in 3D. The simulated movement is similar to movements made by people reaching with a hand-held tool from one point to another with a rod standing in the way (Vaughan et al., 2006). The verisimilitude of the simulation provides encouragement that the posture-based motion planning model is on the right track.

6. HAPTIC TRACKING

One reason to develop a theoretical model is to use it to inspire new questions. One such question was inspired by recognition of the fact that the posture-based motion planning model is primarily concerned with the planning and execution of single-shot, uninterrupted point-to-point positioning movements (i.e., movements that bring the end-effector from one static position to another). Such movements are similar to saccadic eye movements. There are also smooth pursuit eye movements, however. Here the eye smoothly follows a seen, moving stimulus. Can the hand smoothly follow a moving stimulus whose input modality is as closely related to the control of the hand as visually perceived motion is to control of the eye? If so, how can our model account for such behavior?

We pursued this question, wondering whether the specification of goal postures is the only way to move the hand from one place to another. Since the signal that drives the eye in smooth pursuit movements is velocity error whereas the signal that drives the eye in saccadic movements is position error, we reasoned that if the hand can only be driven with reference to goal postures (i.e., position errors with respect to current postures), then smooth pursuit hand movements should be impossible. This was a strong prediction of the posture-based motion planning model. The alternative, weaker, hypothesis was that the hand can also be driven with velocity error signals.

To pursue these alternative possibilities, we initiated a line of research on a task we call *haptic tracking*. Here, the participant is asked to maintain contact with a felt object that may move. Haptic tracking is a common task in everyday life, although it is a relatively novel task for the laboratory (but see Navas, 1964). When people walk while holding hands they maintain light contact, when animals sit on tree limbs they maintain light contact on the branches, and when cooks carry pots from one place to another they may keep the noncarrying hand lightly on the lid. Such tasks suggest that haptic tracking is neither unusual nor particularly difficult. But are such tasks controlled via position error signals or velocity error signals?

To address this question, we studied a task in which the error signal was not positional. We asked participants to close their eyes and maintain contact with a felt moving object whose motion was unpredictable. When the participants' fingertip motion matched the object motion, the shear force on the finger was zero, but when the participant was less successful, the shear force on the finger exceeded zero. Thus, haptic tracking relied on nulling of felt shear forces (i.e., subjects had to move the hand in directions and with magnitudes exactly opposite the shear forces that were felt). The error signal for haptic tracking was thus defined with respect to a nonzero time derivative of position or force, but not position alone.

Could subjects perform haptic tracking tasks? Indeed they could. As reported by Rosenbaum, Dawson, and Challis (2006) subjects excelled at haptic tracking. In fact, they were so good at it that they could perform haptic tracking with two hands at once. Bimanual haptic tracking was possible even when the motions to be tracked were quasi-random or were patterned in ways that are hard to generate without input stimuli that are in motion, such as producing a square with one hand together with a circle with the other hand. Careful control of the apparatus and experimental procedure ruled out the possibility that subjects' hands were being passively dragged or that subjects were predicting the motions to be produced.

How should one interpret such results? One interpretation is that hand movements can be generated in response to velocity or acceleration error signals. Another interpretation is, ironically, that hand movements can be, and perhaps normally are, generated in response to position error signals. The latter interpretation is based on the fact that the hand is often moved from one static position to another, but also, and more importantly, by the fact that participants in our bimanual haptic tracking experiments could move their hands independently, whereas in

conventional bimanual tasks, independence of the two hands is essentially impossible (Kelso, 1984; Swinnen et al., 1998). Evidently, then, use of position error signals cannot be escaped in conventional manual positioning tasks, judging from the fact that when such tasks are bimanual, coupling of the hands sets in, whereas in bimanual haptic tracking tasks, coupling of the hands is all but absent. Insofar as positioning movements are driven by position error signals, there must be a representation of a goal position, as assumed in the posture-based motion planning model.

7. CONCLUSIONS

Progress in motor control research relies on the capacity of researchers to draw useful inferences from the data they possess or seek. One way of directing such inferences is to develop models of motor control that can be tested and successively refined. The posture-based motion planning model is one such model.

We already know that details of the model are wrong. The kinematics of limb positioning movements do not obey the minimum angular jerk law, as assumed in our generation of default movement forms (Hermens & Gielen, 2004). It is also questionable whether joints always start and end their motions at the same time (Hollerbach & Atkeson, 1986). Furthermore, as discussed above in connection with obstacle avoidance, the model does not predict sequential effects such as those observed by Jax and Rosenbaum (2006) or by van der Wel et al (in press). Nevertheless, models, including the posture-based motion planning model, are idealizations. They promote progress to the extent that they drive the search of new facts.

AUTHOR NOTES

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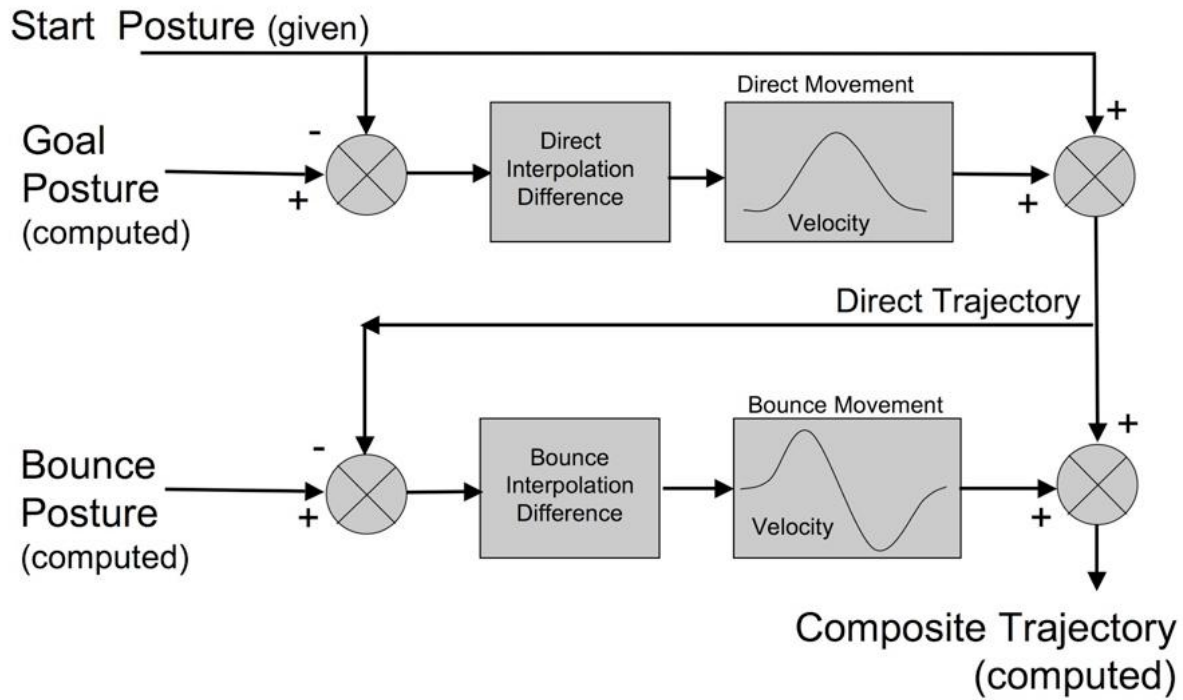


Figure 1. Main components of the posture-based motion planning model for generating an obstacle-avoiding movement given a starting posture, a target to be touched, and an intervening obstacle. From Vaughan et al. (2006).



Figure 2. Grasp height effect. The fourth author, who gave permission to have his photo shown here, serves as a pilot subject, grasping the plunger at the home platform with different grasp heights (white arrows) before moving the plunger to target platforms at different heights (white dashed lines). The first author, who also gave permission to have his photo shown here, was responsible for setting up the target platforms.

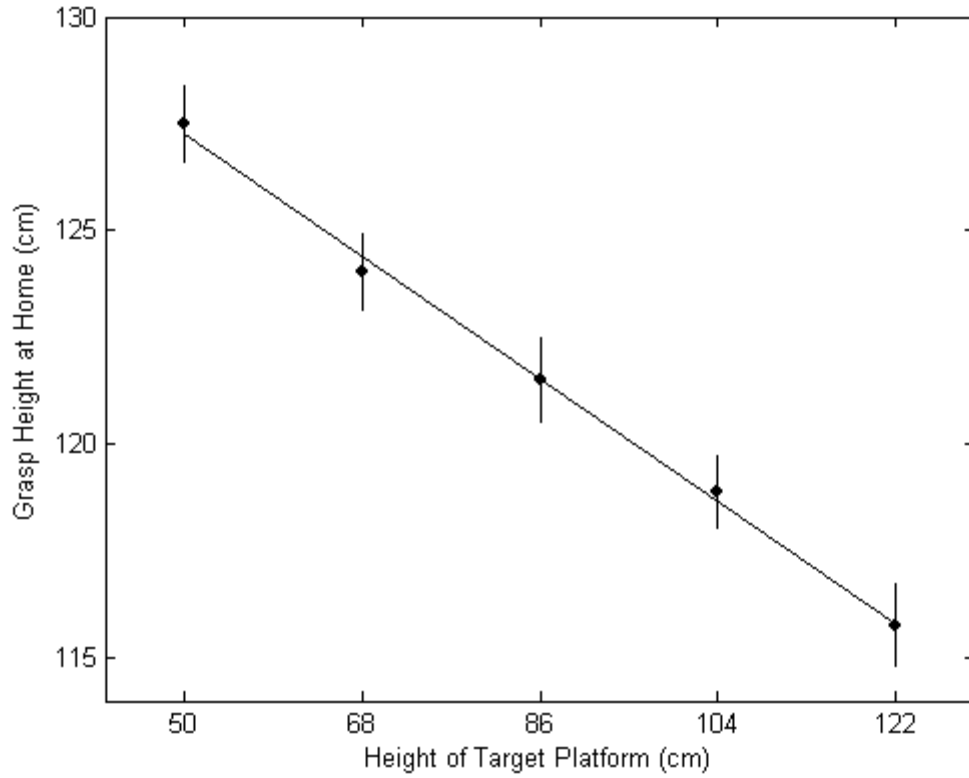


Figure 3. Mean grasp heights (± 1 SE) as a function of target heights. Adapted from Cohen and Rosenbaum (2004).

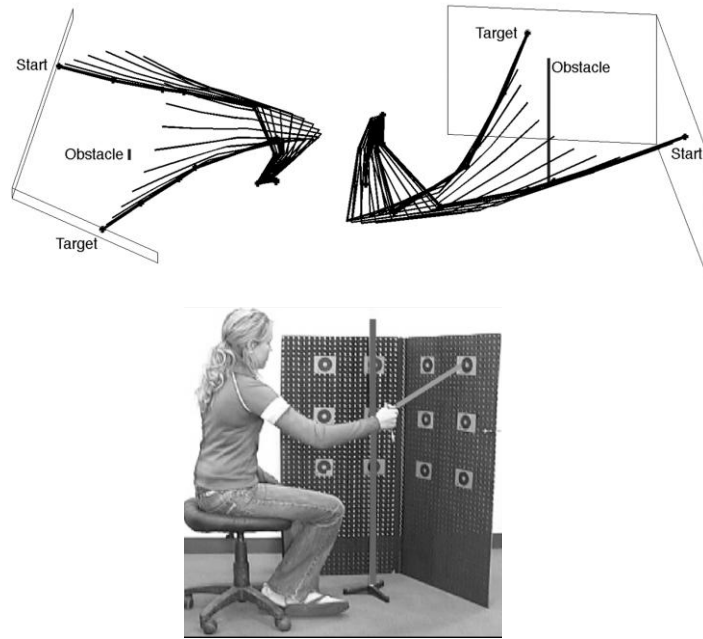


Figure 4. Modeled trajectory in a 3-D workspace as seen from the top (left panel) and as seen from the side (right panel). The trajectory that was modeled came from a seated young adult (bottom panel) who moved a hand-held tool from a start location on one 24 × 48 inch panel to a target location on an adjacent panel of equal size while avoiding an intervening obstacle (a rod that stood between the two locations). From Vaughan et al (2006).