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Control of human arm movements in two dimensions: paths and joint control in avoiding simple linear obstacles

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Abstract. In order to examine path planning and the control of redundant degrees of freedom in the human arm, the movements of the shoulder, elbow and wrist were recorded as subjects moved a pointer to a target and avoided a simple obstacle. With respect to joint control, the results show that the extra degree of freedom provided by the wrist is incorporated into target movements in a systematic manner for both large and small obstacles; it is not used only when there is no geometrical alternative. For the wrist, two strategies are apparent, depending upon the length of the obstacle. Wrist extension predominates for shorter obstacles, while flexion or extension and flexion predominate for longer obstacles. These wrist movements shorten the effective length of the distal segments (lower arm plus hand and pointer) and thus reduce the excursion required at the proximal joints. In part, they correspond to assuming the most comfortable arm configuration at each point in the new path necessitated by the obstacle and can be described by static cost functions. However, wrist extension is also used to move the hand and pointer away from the obstacle as shoulder and elbow movements carry the wrist itself towards the obstacle. Wrist flexion is also used to move the pointer tip rapidly past the obstacle. These components, which cannot be explained by static cost functions alone, confirm for the human arm the hypothesized use of redundant degrees of freedom in obstacle avoidance. With respect to path planning, the results show that the minimum distance between pointer and obstacle remains fairly constant over a large range of obstacle lengths; this relative invariance is interpreted to support the hypothesis that workspace coordinates are important for movement planning. However, minimum distance and several other path parameters do depend significantly on the orientation and location of the movement in the workspace. This inhomogeneity implies that movement planning does not occur exclusively in workspace coordinates; it suggests an influence of joint space criteria. In frontal movements, for example, the systematic decline in the minimum distance with increasing obstacle length is interpreted as a compromise reducing the amount of extra joint movement and the discomfort of arm configurations.

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Introduction

The shoulder, elbow and wrist of the human arm provide seven degrees of freedom for movement in three dimensions, so the arm has redundant degrees of freedom for simple pointing tasks. Thus, a subject can use many different arm configurations to point to a given target as long as the target is not at the margin of the reachable space. This is also true when shoulder, elbow and wrist are all free to move and the finger tips are to be placed at a particular position in the plane of the arm. In contrast, when such movements in a plane are carried out using only two joints, the available degrees of freedom equal the number required by the task, so each position of the hand or finger tips corresponds to one and only one combination of joint angles.

Pointing movements under non-redundant conditions have been extensively investigated (review Georgopoulos 1986; Hogan 1988), but the redundant case is less well studied. Because the control problem is underconstrained, a system with redundant degrees of freedom cannot be controlled in a predictable way unless additional constraints are imposed. Thus, one important question in motor control is how humans utilize redundant degrees of freedom. One possibility, discussed by Bernstein (1967) in relation to learning new movements, is simply not to use a degree of freedom unless the task demands it, i.e. unless the redundancy disappears. Another possibility is to use redundant degrees of freedom to optimize additional criteria. For example, when subjects are asked to position one arm comfortably in the horizontal plane through the shoulder, the configurations chosen can be described by assigning independent cost functions to each joint and choosing the arm configuration which places the finger tips at the desired position and provides the lowest total cost (Cruse 1986). Studies of simple pointing movements under the same conditions show that the cost functions determined under static conditions also influence joint configurations during movement (Cruse and Brüwer 1987; Cruse et al. 1990).

However, these studies do not address the question of how additional degrees of freedom are utilized under more complex conditions. Extra degrees of freedom are potentially useful in two situations. One is when the task specifies not only the position but also a particular configuration for the hand, as in grasping objects. The second is when movements are carried out in the presence of obstacles. The latter is considered here. In the presence of obstacles, extra degrees of freedom help in three ways. First, they expand the workspace by enabling the arm to reach around and behind obstacles. Second, they may provide alternative ways to avoid the obstacle. Third, as in unobstructed pointing, they can be used to optimize additional parameters.

To avoid an obstacle, a path must be found which carries the hand past the obstacle and then appropriate joint configurations must be specified which move the hand along the chosen path. When no redundant degrees of freedom are present, solving the first problem automatically solves the second. Under these conditions, human subjects apparently guide the movement through an appropriate intermediate position located near the obstacle (Abend et al. 1982). The path is constructed as a smoothed combination of a straight or gently curved segment from the start to the intermediate point (a "via point" in the terminology of Flash and Hogan 1985), a segment of greater curvature near the via point and a second straight or gently curved segment from there to the target. Once the movement duration and the initial, final and via points are specified, the complete trajectory can be obtained by optimizing one or more criteria such as jerk (Hogan 1984; Flash and Hogan 1985), torque change (Uno et al. 1989) or other parameters discussed by Nelson (1983).

In general, finding a path can be done either in workspace or joint coordinates. However, most experimental results to date indicate that humans plan movements in terms of the end-effector movement in workspace coordinates (e.g. Morasso 1981; Hogan 1988; Lacquaniti 1989). If this is true, then paths should be invariant with respect to translation and rotation in workspace (Flash and Hogan 1985; Flash 1990).

The experimental studies of obstacle avoidance mentioned above focused on characteristics of paths and trajectories in the non-redundant situation, but both Abend et al. (1982) and Flash and Hogan (1985) mention supplementary experiments showing that the trajectories do not change when the wrist is free to move. The goal of the present research was to provide a systematic description of the paths and arm configurations chosen by human subjects using all three arm joints to move a pointer around simple obstructions. The analysis presented here focuses on kinematic aspects of the path followed by the tip of the pointer and on the way the movement is apportioned among the three joints. In particular, it considers the following questions: (1) to what extent paths in workspace are invariant, (2) whether humans actually utilize the redundant degrees of freedom available in the arm, and (3) whether the cost function model provides a sufficient description of joint configurations used in moving along the selected path.

Materials and methods

Eight subjects made movements with the right arm held in the horizontal plane passing through the shoulder (Fig. 1). The movements were performed with the subject seated and the right shoulder resting in a U-shaped holder at the origin of the Cartesian coordinate system for the workspace. The right hand gripped the vertical handle of a manipulandum moving over a table located slightly below shoulder level. The handle was fitted with a pointer representing an extension of the fingers. Thus, the position of the pointer tip was controlled by rotating the shoulder, elbow and wrist joints about their vertical axes. The path of the movement is defined as the path taken by the pointer tip.

The manipulandum was a modification of other inverted hand-position transducers (Morasso 1981; Abend et al. 1982) which allowed all three joint angles to be recorded. It consisted of a freely rotating handle and pointer mounted on two links, which formed an approximate mirror image of the subject's arm (Fig. 1). Unlike previous designs, the elbow of the manipulandum was placed on the same side as that of the subject in order to improve visibility of the workspace. The proximal segment, a 54–cm × 3–cm × 5–cm hollow aluminum beam, was 51 cm long from axis to axis. The distal segment, a 65–cm × 2.5–cm × 2.5–cm hollow aluminum beam, was 63 cm long from axis to axis. The wall thickness was 2 mm. To further lighten the manipulandum, holes of 2 cm diameter were cut in a honeycomb pattern at 3–cm intervals in the upper and lower surfaces of the proximal segment and at 2.5–cm intervals along the sides of the proximal segment and all four sides of the distal segment. The proximal segment was mounted on an axis located opposite the shoulder of the subject, (0.0, 109.5) in centimetres in shoulder coordinates; the distal segment was suspended at a height of 15 cm above the table. The handle was a hollow plastic cylinder of 3 cm diameter, mounted below the tip of the distal segment. Attached to its lower end was a 23–cm pointer (weight 10.9 g) cut from a 1–mm–thick aluminum sheet. All three axes of the manipulandum were mounted on twin ball bearings. Together, handle and pointer weighed 109 g. Their moment of inertia was ca. 3×10^{-3} kg · m^2. The distal segment weighed 330 g; together with the handle, the moment of inertia around the elbow of the manipulandum was ca. 0.2 kg · m^2. The proximal segment weighed 764 g. The total weight of the manipulandum was 1.2 kg. With the distal segment at right angles to the proximal segment, the moment of inertia of the whole was ca. 0.5 kg · m^2. The separation between the base of the pointer and the table ranged from none to as much as 1 cm in different areas of the workspace. In the former case, the blunt, soft plastic tip forming the base of the handle glided over the surface of the table, a plate of glass (90 cm × 90 cm × 4 mm) covering the workspace. As a rule, the handle was not in contact with the table when a subject held or moved the manipulandum.

The configuration of the manipulandum was registered by precision, low-torque potentiometers (Megatron MCP40, 50 kΩ, linearity ±0.1%) measuring the rotation at the base, middle joint and handle. The signals from the potentiometers were sampled at 70 Hz by an analogue-digital (A/D) converter (AD-12 Bit; Kolter Electronic) in an AT-compatible 386 computer. The raw data were filtered using a 7-point moving average (relative weights 1,2,3,3,3,2,1; Hamming 1977). These signals allowed the computer to determine the position of the pointer tip to within a few millime-

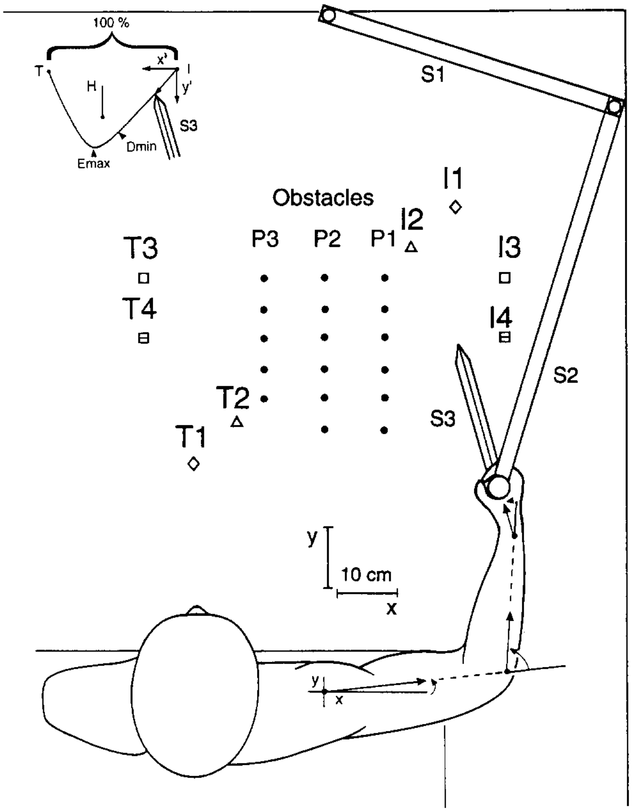

Fig. 1. Experimental setup and the task definition in workspace as viewed from above. With the right arm elevated horizontally, the subject moved the handle of a two-link manipulandum (*S*1, *S*2) over a table located slightly below shoulder level. The task was to move the tip of the pointer (*S*3) from one of four initial positions (*I*1–*I*4) to the corresponding target (*T*1–*T*4) while avoiding a single, linear obstacle placed at one of three different locations and intruding to different degrees into the straight path. The three locations along the path (*P*1–*P*3) and the proximal ends of the obstacles tested for one movement in the frontal plane (*I*4–*T*4) are shown. The coordinate system for the workspace (x, y) is centered at the subject's shoulder. In order to compare different movements, paths were transformed into coordinate systems (x', y') located at the initial position and aligned with the direction to the target (see *inset at upper left*). Potentiometers on the three axes of the manipulandum permitted the computer to determine the position of the tip and the angles of the three arm joints. Joint angles are defined as external angles, as shown. The *inset* shows a typical path and indicates the parameters analysed: *Dmin* the minimum distance between path and the end of the obstacle end (H) and *Emax* the furthest excursion from the straight path (*Emax*). For some statistical comparisons among different movements, distance measures were normalized relative to the straight distance between initial and final positions (100%)

tres. A calibration check preceding each measurement ensured that the computed tip position was within the radius of the target light-emitting diodes (LEDs; 2.5 mm). The noise in the measurements for a subject holding the arm in different positions spanning the workspace corresponded to standard deviations of less than 2 mm in tip position. Variation in the systematic error in the measured tip position with changes in the x coordinate was less than 3 mm across the entire workspace and less than 0.5 mm in the central field where obstacles were located. Variation in the systematic error with changes in the y coordinate was less than 3 mm overall and less than 1.5 mm for the area occupied by obstacles proximal to the distal frontal movement.

These position measurements were then transformed into Cartesian x,y-coordinates relative to the shoulder joint (0,0). The x-coordinate represents the lateral position and the y-coordinate the distance in front of the shoulder. For most diagrams and statistical comparisons, positions of the pointer and any obstacle are expressed in coordinates aligned parallel (x') and perpendicular (y') to the straight path and values are normalized as percentages of the straight distance between initial position and target. For convenience, the positive direction for y' is towards the subject, so that larger obstacles are more positive.

The data on the position and angle of the handle relative to the shoulder joint, together with the measured lengths of the subject's upper arm (acromion to lateral epicondyle of the humerus), lower arm (epicondyle to styloid process of the radius) and hand (styloid process to handle axis), allowed the computer to determine the angles of the shoulder, elbow and wrist joints. The noise in the measurements for a subject holding the arm in different positions corresponded to standard deviations of less than 0.5° for shoulder and elbow angles and less than 1° for wrist angles. These data were recorded by the computer and stored on disk for further analysis.

The computer controlled the presentation of starting points, targets and obstacles by turning on LEDs (5 mm diameter) mounted in the surface of the table below the glass plate. In the experiments reported here, the subjects were asked to move the pointer from an initial position to a target while avoiding a "virtual" obstacle defined by three to seven LEDs in a line perpendicular to the straight path (Fig. 1). (The LEDs did not represent a physical barrier.) Initial positions and targets were located symmetrically on either side of the midline of the workspace. Four pairs of initial positions and targets were tested (Fig. 1). The two frontal movements were between pairs of points located 60 cm apart in frontal planes at distances of either 58 cm or 68 cm in front of the shoulder. The two diagonal movements were between pairs of points located 40 cm and 60 cm apart along the same diagonal: from (14.0, 72.2) to (−14.0, 43.8) and from (20.0, 79.3) to (−20.0, 36.7), respectively. In order to maximize visibility of the targets and obstacles and to reduce the number of movements and data to a manageable size, this initial study only considered movements from right to left.

Obstacles differed in their location along the straight path and their length perpendicular to the path. They were presented using three lines of LEDs arranged perpendicular to the movement direction and located at the midpoint (P2 in Fig. 1) and at offsets of 10.0 cm towards the start (P1) and towards the target (P3). For the movements of 60 cm these positions corresponded to 33, 50, and 67% of the straight path. The same offsets were used for both diagonals, so, for the shorter movement, the three positions corresponded to 25, 50 and 75%. The lengths of the obstacle perpendicular to the movement direction varied in 5-cm intervals between −10.9 cm distal and 25.0 cm proximal to the straight path. Expressed as percentages of the straight distance, this range corresponded to −27 to 50%.

The required movements were defined in a control file and presented by the computer in random order. For each movement, the computer first turned on the LED at the initial position. When the subject moved the pointer to this position, the computer turned on the LEDs of the target and any obstacle. (The approach criterion was no more than 2.5 cm from the center of the LED for the first three subjects and no more than 0.5 cm for the rest. The latter corresponded approximately to the natural accuracy shown by all subjects.) When the subject indicated readiness to begin a movement, the computer issued an acoustic signal and began recording data. In order to ensure an adequate record of the initial position, the subject was instructed to pause briefly after the start signal before making a movement. Recording continued until the subject indicated the movement was completed. If the subject and the experimenter judged the movement to be satisfactory, the data were retained for permanent storage; otherwise the trial was erased and the movement was repeated at a later time in the random sequence. Trials were repeated if the pointer tip passed over the obstacle, the movement began too quickly after the start signal, or the subject was dissatisfied with the accuracy of the final approach to the target. Most subjects never hit the obstacle; no more than about three trials per session were ever repeated for other reasons.

The instructions to the subject were simply to move the pointer tip comfortably, as in freehand pointing, from the initial position to the target in such a way that the pointer tip and the subject's arm did not pass over any obstacle which might be present. No demand was made concerning movement speed or accuracy. However, the latter may have been implicitly conditioned by the required proximity to the initial LED before a trial could begin.

Three sets of measurements were made from each of eight subjects (six men, two women, ages 23–43). Subjects unfamiliar with the apparatus were given practice on a set of 22 unobstructed movements spanning the entire workspace. The initial set of tests did not include the longer diagonal movement (see Fig. 1) and all obstacles extended at least as far as the straight path. In the second set, the longer diagonal movement was added. In the final set, obstacles located at two positions distal to the straight path were included. Together with control tests without obstacles and a two-line obstacle which will not be considered here, a total of 47 movements were required of the subjects in the first session, 62 in the second, and 86 in the third. Except where noted, results from all subjects were at least qualitatively similar. Two additional subjects were tested but omitted from the final analysis because their mean movement durations were considerably longer than those of the other eight (ca. 2.5 s versus under 1.5 s).

In order to compare arm configurations during movements with static arm configurations, subjects were also asked to point to each of 30 points in a grid covering the workspace. The stationary arm configurations were recorded as before. Then parabolic cost functions, specifying postural cost or discomfort as a function of joint angle, were determined for each joint using simulated annealing as described by Cruse et al. (1990). In brief, simulated annealing (Kirkpatrick et al. 1983) is an optimization technique which is useful when the optimization problem cannot easily be solved analytically and local optima may be present. Here, the parabolic cost function for each joint is defined by the angle of minimum cost and the slope, so six parameters were fitted. The simulated annealing routine repeatedly generates a set of six parameters, computes for all targets the corresponding joint angles specified by the minimum cost principle and uses the total sum of the squared deviation from the measured joint angles to rate the sextuple. The goal is a sextuple which minimizes this deviation. A temperature parameter, which decreases in successive iterations, controls the probability of accepting a sextuple giving a larger error than the current best sextuple; this can enable the search to move out of local minima.

The subsequent analysis proceeded in several steps. A cursor was used to sample and store desired data points from plots displayed by the computer. Two types of plot were analyzed. First, the computer displayed plots of the tip trajectory and any obstacle in the x,y-coordinates of the workspace. From these plots, the point of nearest approach to the obstacle and the point of maximum excursion from the straight path were entered into data files. (More complicated parameters can be chosen to describe the path, but these two were selected to characterize the safety margin in avoiding the obstacle and the change from the more or less straight paths taken in the absence of obstructions. Moreover, they are easily measured and, unlike the jerk integral or path length, do not vary with the criteria used to determine the beginning and end of a movement.) Then the computer displayed plots of joint angles versus time. From these plots, the initial and final angles together with up to three turning points were entered into data files. The turning points considered were the largest excursion from the direct line between initial and final angles plus one turning point preceding and one following this largest excursion. These data files were preprocessed to perform the conversion and normalization of path and obstacle parameters into coordinates aligned parallel (x') and perpendicular (y') to the straight path, to convert temporal values into differences relative to the beginning of movement in the shoulder and to calculate relative joint angles and several indices described below.

Results

Paths of the pointer tip in workspace

Paths were analysed to determine: first, how they depend on the geometry of the task; second, whether they are invariant with respect to location in the workspace; and third, what features, if any, are subject to change.

In the absence of an obstruction, movements of the pointer tip followed an almost straight path between initial and final positions (Fig. 2). As a rule, any curvature in the path was directed away from the elbow, although small curvatures in the opposite direction sometimes occurred early in the movement. In addition, small corrections often occurred at the end of the movement when the tip was already within a few centimetres of the target. These final corrections usually involved flexion of the wrist, i.e. the final approach was made from the distal or right side of the target (e.g. Fig. 3a,c). In such unobstructed movements, the tangential velocity of the tip along the path generally followed a smooth, bell-shaped curve with a single peak (Fig. 2). This peak was often slightly asymmetric, with the acceleration in leaving the initial position occupying less time than the deceleration and any final corrections in approaching the target. Such asymmetry generally occurs for movements under visual control where accuracy is required (Beggs and Howarth 1972; Soechting 1984; Georgopoulos 1986).

The presence of an obstruction between initial and final positions necessarily forced the pointer to follow a curved path proximal to the obstacle (Fig. 2), i.e. the direction of curvature was opposite to that usually present in the absence of an obstruction. Moreover, the length of the obstacle determined the necessary minimum excursion from the straight line. For a given obstacle, the shortest path, similar to that of Fig. 3d, would contain two straight segments connecting initial and final positions to a point of furthest excursion located just proximal to the end of the obstacle. Actual paths followed by the pointer differed from the shortest path in three qualitative respects.

First, as in other experimental conditions (Abend et al. 1982; Flash and Hogan 1985), the turn around the obstacle was more rounded. The most common form contained two nearly straight or gently curving segments leading to and from the obstacle, connected by a segment of increased curvature near the obstacle. Such paths were especially common for movements in the frontal plane. Two variants also occurred, particularly for diagonal movements. In the more common variant, the path was still more rounded, with nearly constant curvature or with several changes in the degree of curvature (e.g. Fig. 3b). Less frequently, the segment to or from the obstacle curved towards the obstacle, so there was a reversal in the direction of curvature (Fig. 3b–d).

Second, as in unobstructed movements, small corrections often occurred in the final few centimetres of movement (e.g. Fig. 3a,c). These resembled the "little hooks" referred to by Flash (1987). Their length could be as much as 5 cm. In these corrections the tip usually approached the target from the distal or right side. Shoulder, elbow

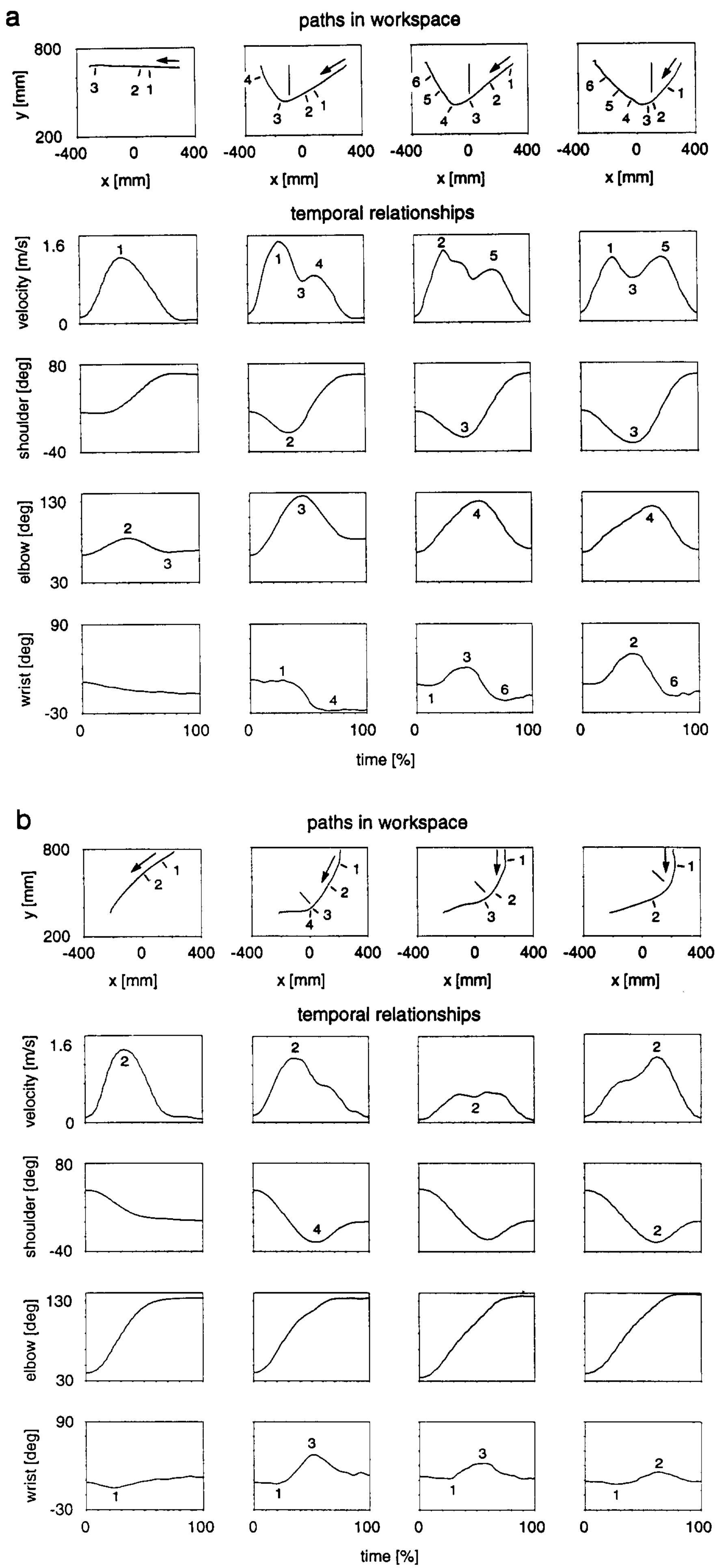

Fig. 2a,b. Examples of paths, tangential velocities of the pointer tip and joint movement profiles for movements in the presence and absence of obstacles. The curves show the path followed by the tip of the pointer in the workspace for typical movements in a frontal plane (**a**), (position I3–T3) and along a diagonal (**b**), (position I1–T1) with no obstacle (*first column*) and with obstacles at three positions along the path. The origin (0,0) for the workspace coordinates is at the shoulder. The four curves *below each path* show the tangential velocity of the pointer tip and the angles assumed at the shoulder, elbow and wrist. Movement duration is normalized to 100%. To indicate the relationships between the path and the changes in velocity and joint angle, numbers are added to mark corresponding points

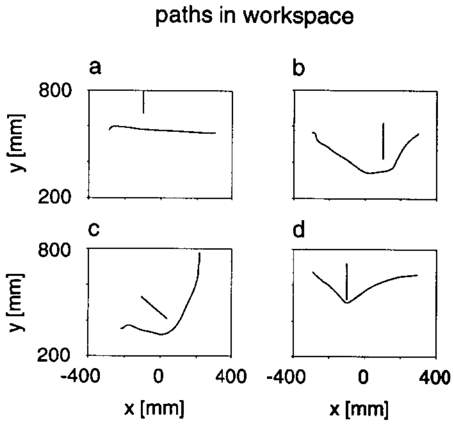

Fig. 3a–d. Examples of less common paths. As in Fig. 2, the curves show the movement of the pointer tip in the workspace with the origin (0,0) at the shoulder. The features illustrated are as follows: **a** distal curvature and pronounced final hook in the presence of an obstacle distal to the straight path; **b** two distinct changes in curvature near the obstacle; **c** a final correction made from between the obstacle and the target; and **d** an unusually slow movement with a close approach and sharp turn as well as distal curvature in the approach segment

and wrist movements could all contribute to these corrections, but small flexions of the wrist were commonly involved. A final approach from this preferred direction even occurred for diagonal movements with large obstacles near the target, i.e. the tip approached the target from a position between target and obstacle (Fig. 3c).

Third, the tangential velocity of the tip along the path no longer followed a bell-shaped profile: in accord with the literature (Abend et al. 1982; Flash and Hogan 1985), two peaks were often present with the intervening trough coinciding with the segment of increased curvature in the path near the obstacle. This structure was particularly evident in the first session of one subject in which the curvature at the obstacle was unusually sharp (e.g. Fig. 3d) and the movements were unusually slow (overall mean duration of nearly 3 s as opposed to 1–1.5 s for the subjects included in the main analysis).

Most important, examples such as those of Fig. 2 suggested that paths and their relationship to the obstacles differed depending on movement orientation. This qualitative impression was explored quantitatively using two parameters to characterize the path and its relationship to the obstacle: the point of closest approach to the obstacle and the turning point or point of furthest excursion from the straight path between initial and final positions. These positions usually differed.

Factors affecting the size and location of the excursion from the straight path

For comparison with movements around obstacles, it was first necessary to characterize unobstructed movements under the present experimental conditions. For all four pairs of initial and final positions, most unobstructed movements followed a path with a slight curvature away from the elbow (e.g. Fig. 2). The mean value for the furthest excursion from the straight path (horizontal line in Fig. 4) was negative, i.e. directed away from the elbow, and significantly different from zero (mean and standard deviation equal to -26.2 ± 20.3 mm, or $-4.7 \pm 3.5\%$ of the straight distance, $n = 104$, $t = 13.2$, $P < 0.0001$). All three deviations at the positions where obstacles other-

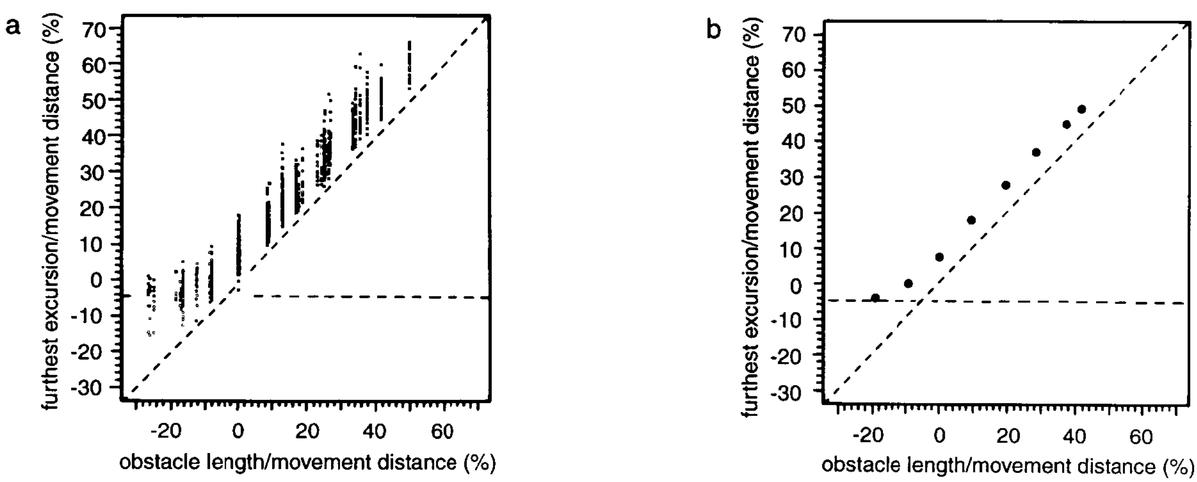

Fig. 4a,b. The furthest excursion from the straight path as a function of obstacle length. The maximum excursion in either direction (y' for Emax) and the length of the obstacle (y' for the proximal end of the obstacle) are both plotted as percentages of the length of the straight path between initial and final positions. Individual values (**a**) and means for eight classes of obstacle lengths (**b**). Ninety-five percent confidence intervals for the means in **b** are smaller than the size of the symbols. For obstacles smaller than -15%, the furthest excursion is constant, negative and not significantly different from that for the unobstructed movements, indicated by the *horizontal line* at -4.7%. For obstacles larger than -5%, the excursion increases linearly with obstacle length. (The path near the obstacle must be proximal to the end of the obstacle if the two do not intersect. As a rule, this was also the furthest excursion, so virtually all points lie above the dashed 45° line corresponding to the proximal end of the obstacle. The two exceptions are paths which curved proximally around small obstacles and then made a larger, distal excursion.) The number of observations in the individual means **b** varies from 48 to 264 wise occurred were also negative and significantly different from zero (all at $P<0.001$).

Path asymmetry was evident in the location of the point of furthest excursion from the straight line. This parameter differed according to the movement tested. For the two diagonal movements, the curvature was more symmetric. On average, the furthest excursion occurred at $50.4 \pm 17.5\%$ ($n = 24$) along the straight path for the longer movement and $53.1 \pm 10.6\%$ ($n = 32$) for the shorter movement. These values were not significantly different and neither value was significantly different from 50%, the midpoint. For both frontal movements, the mean point of furthest excursion was at $63.1 \pm 12.7\%$ ($n = 48$), significantly into the second half of the movement (difference from 50%: $t = 7.1$, $P<0.0001$). Within subject means for different movements varied by as much as $\pm 20\%$ from the overall means.

In successfully avoiding an obstacle which intersects the straight path, the size of the proximal excursion must exceed the length of the obstacle. With two exceptions for small obstacles, the proximal excursion was also the larger excursion, so the maximum excursion increased nearly linearly with the length of the obstruction (Fig. 4). When both excursion and obstacle length were expressed as percentages of the straight distance, the slope of the regression was 1.02 ± 0.01 (estimate and standard error, $r = 0.96$, $n = 1191$) for obstacles which intersected the straight path. The regression was quite similar when only obstacles located at the midpoint (position 2) of the straight path were considered (slope 1.02 ± 0.01, $r = 0.97$, $n = 439$).

Given that the paths in the absence of an obstacle curved distal to the straight line, one would expect that obstacles ending slightly more distally might still influence the movement. This was true for obstacles ending at -50 mm; they caused the path to curve proximally rather than distally (Fig. 4). For obstacles ending at -100 mm, the mean maximum excursion was distal to the straight path and, although it was still slightly more proximal than that for movements with no obstacle, the difference was not significant.

Besides the dominant effect of obstacle length, the size of the maximum excursion was also affected by movement orientation and several other factors. This was shown using the difference between the y'-coordinates of the point of maximum excursion and the proximal end of the obstacle. The analysis was limited to obstacles between 0 and 155 mm in length which could be tested for all movements. (For obstacles intersecting the straight path, the length of the obstacle did not have a large effect on this measure: means remained fairly constant at 43–47 mm.) Both subject and, more important, movement orientation (Fig. 5) were highly significant factors ($P<0.001$). Subject means ranged from 30 to 59 mm. In all but one subject mean excursions were on the order of 11 mm larger for frontal movements than for diagonal movements. In all subjects the excursion for the distal frontal movement was on the order of 7 mm greater than that for the proximal movement. Means for both diagonal movements were similar and less than those of either frontal movement (Fig. 5). For diagonal movements, the

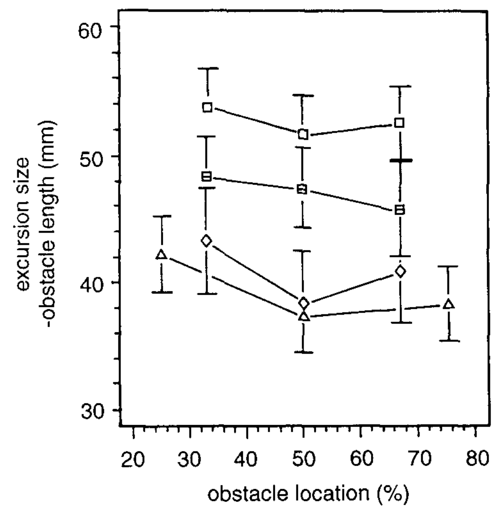

Fig. 5. The furthest excursion as a function of obstacle location along the path. The extent to which the furthest excursion exceeds the obstacle length (y' for Emax $-y'$ for the proximal end of the obstacle) is plotted as a function of obstacle location along the path (x' for the obstacle) for each of the four movements tested (see Fig. 1 for the definition of *symbols*). Obstacle locations are given as percentages relative to the length of the straight path. (Due to the use of the same obstacles for diagonal movements of two different lengths, data points occur at 25, 33, 50, 67 and 75%.) The means and 95% confidence intervals are from an analysis of variance which included obstacle lengths between 0 and +155 mm (38%) and used obstacle length as a covariate. Longer obstacles were omitted because they could not be tested at all three positions. The number of observations in individual means ranges from 64 to 96

difference increased significantly by several millimetres as obstacle length increased. The location of the obstacle along the path had a smaller but still significant influence ($P<0.001$) on the size of the excursion; excursions for obstacles at position 1 were, on average, 4 mm greater than for those at the other positions. This difference was significant only for the two diagonal movements together and for the shorter of these two alone.

The position of the maximum excursion along the path (x') was usually near but not right at the proximal end of the obstacle (Figs. 2,6); it was affected by both movement orientation and obstacle location along the path. Comparing frontal to diagonal movements, Fig. 6 shows that for each obstacle location the furthest excursion in frontal movements occurred later in the path. In frontal movements, the furthest excursion occurred after passing obstacles at positions 1 and 2 (points above the diagonal in Fig. 6) and near the end of obstacles at position 3. In diagonal movements, the furthest excursion occurred slightly past obstacles at position 1 and before obstacles at positions 2 and 3 (points below the diagonal in Fig. 6). Thus, for the two positions away from the middle position, the furthest excursion tended to be either at the obstacle or on the side closer to the midpoint of the straight path. All subjects showed qualitatively similar changes with obstacle location and movement orientation, but individual differences were significant. Subject means computed over all movement orientations and all obstacles intersecting the straight path ranged from 48 to 55%. The interaction between movement ori-

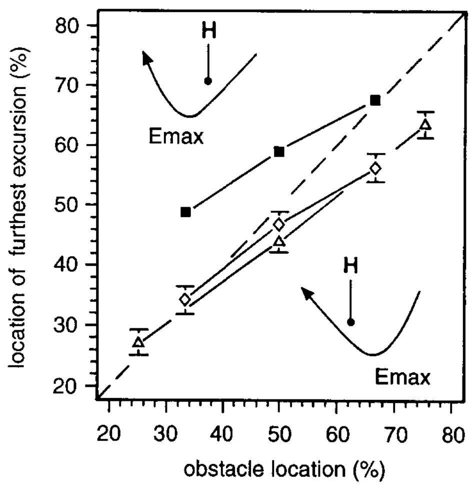

Fig. 6. Location of the point of furthest excursion along the straight path as a function of obstacle location. The locations of the furthest excursion (*x*' for *Emax*) and the obstacle (*x*' for obstacle) are plotted as a percentage of the straight distance. Means and 95% confidence intervals are plotted separately for the two diagonal movements (△,◇) and, since the difference was not significant, for the combination of both frontal movements (■). The means are calculated for obstacles extending at least as far as the straight path. The number of observations ranges from 64 to 240. For *points below the diagonal*, the furthest excursion occurs before the tip passes the obstacle, as shown in the *inset at the lower right* (*H* is the obstacle); for *points above the diagonal*, the furthest excursion occurs after the tip passes the obstacle, as shown at the *upper left*

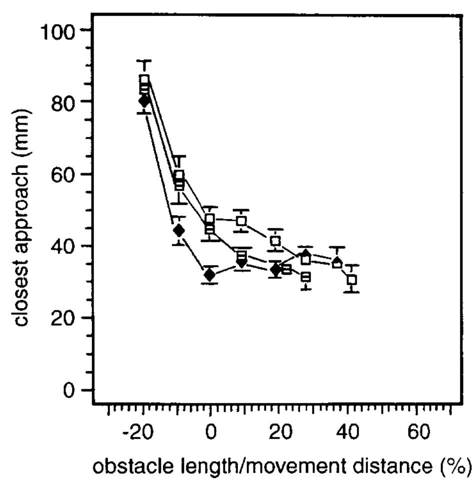

Fig. 7. The closest approach as a function of obstacle length and movement orientation. Means and 95% confidence intervals for the minimum distance, in millimetres, between the path of the pointer tip and the end of the obstacle are plotted versus the length of the obstacle (*y*' for the obstacle end). For frontal movements, the closest approach decreased monotonically with obstacle length; for obstacles of the same relative length, the minimum distance was larger for the distal movement (□) than for the proximal movement (⊟). However, for the same absolute obstacle position in the workspace, minimum distances did not differ, as can be seen by comparing each mean for the proximal movement with that two positions to the right for the distal movement. (The obstacles representing a length of 100 mm for the distal movement are the same light-emitting diodes (LEDs) as those representing a length of 0 mm for the proximal movement, and so forth.) Values for the two diagonal movements did not differ and are plotted together (◆); the increase for obstacle lengths greater than zero was statistically significant. Numbers of values in the different means range from 24 to 120

entation and subject was also highly significant, indicating that, although the orientation influence was present in all subjects, its strength differed from one subject to another. For each obstacle location, the variance in the location of the furthest excursion decreased as obstacle length increased.

Factors affecting the closest approach to the obstacle

Because the turning point usually did not correspond to the point closest to the obstacle, the latter was considered on its own. The tip of the pointer almost always followed a diagonal path past the obstacle, so the closest approach was to the proximal end of the obstacle, the reference point for measuring the minimum distance.

Figure 7 shows that the minimum distance was affected by obstacle length and by movement orientation. The most interesting results concern obstacles which intersect the straight path (non-negative abscissa values). To a first approximation, the closest approach remained surprisingly constant for these obstacles: means only varied between 3 and 5 cm. However, movement orientation again played a role. For frontal movements, the closest approach decreased monotonically with increasing obstacle length. At each obstacle length, the closest approach was nearer for the proximal movement. However, means for obstacles at the same absolute locations in the workspace did not differ. (In Fig. 7, compare each mean for the proximal movement with the mean two to the right for the distal movement.) For diagonal movements, the minimum distance was least for obstacles ending on the straight path and then increased slightly with increasing obstacle length. The pointer approached small obstacles more closely in diagonal movements than in frontal movements, but this difference disappeared for longer obstacles.

Three obstacle endpoints were common to the test sets for frontal and diagonal movements. For one, the midpoint of the straight path for the two diagonal and the proximal frontal movements, the closest approach was significantly larger for the two frontal movements. For the second, the most proximal point in the middle row (P2 in Fig. 1) and geometrically the most restrictive obstacle, differences according to movement direction were not significant. For the third, the point at 150 mm in the middle row for the diagonal movements, the closest approach was significantly smaller for the frontal movements ($P<0.005$); the mean minimum distance was 35 mm for diagonal movements versus 30 mm and 28 mm for the distal and proximal frontal movements, respectively.

For the obstacles ending distal to the straight path (negative abscissa values in Fig. 7), the minimum distance increased rapidly. This is not surprising. The slope should be about -1 if the subjects simply follow the straight path for all such obstacles, regardless of how far outside the straight path they lie. The closest approach

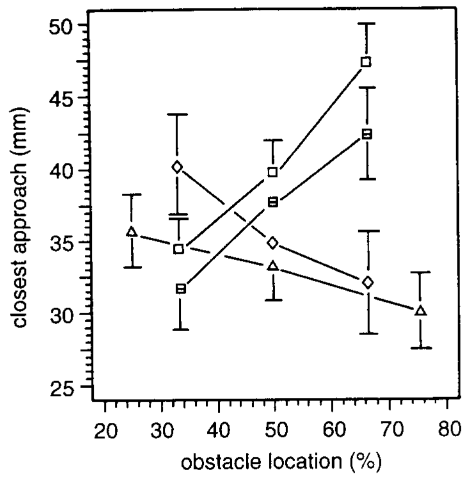

Fig. 8. The closest approach as a function of obstacle location. Means and 95% confidence intervals for the minimum distance, in millimetres, between the path of the pointer tip and the end of the obstacle are plotted versus the location of the obstacle along the path (x' of the obstacle), given as a percentage of the straight path. Only data for obstacles extending at least as far as the straight path are included in the means. Numbers of observations range from 64 to 144

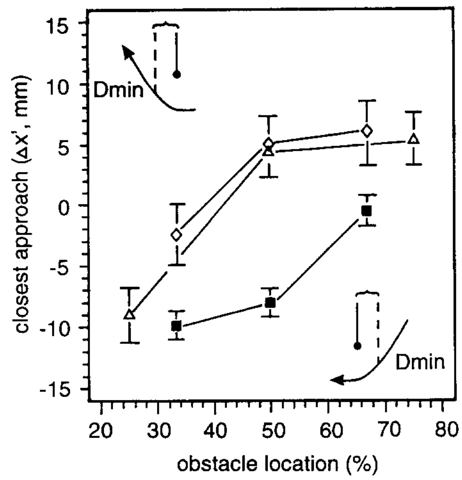

Fig. 10. Location of the closest approach relative to the obstacle as a function of obstacle location. The *abscissa* shows the location of the obstacle along the straight path (x'); the *ordinate* shows the difference in x' between the point of closest approach (*Dmin*) and the location of the obstacle. Negative, positive and zero differences correspond to points of closest approach before the obstacle (*upper inset*), after the obstacle (*lower inset*) or on the line of the obstacle. Values for the two movements in the frontal direction are grouped together (■) because they do not differ; values for the two diagonal movements, long (◇) and short (△), are shown separately because the abscissa values differ. Only data for obstacles greater than −5% are included. The number of values in the individual means ranges from 64 for the long diagonal to 240 for the frontal movements

also varied according to the location of the obstacle, and this relation again differed between diagonal and frontal movements (Fig. 8). As the obstacle shifted along the path towards the target, the means for the minimum distance from the obstacle increased linearly for the frontal movements and decreased linearly for the diagonal movements.

The subject means, calculated for obstacles intersecting the straight path, differed by small but highly significant amounts: they ranged from 23.5 ± 9.6 to 49.0 ± 15.5 mm (Fig. 9b). Subject means for the closest approach were positively correlated with those for the size of the furthest excursion (Fig. 9b) and negatively correlated with means for movement duration (Fig. 9a). Changes in the approach distance over the three sessions were significant but variable from subject to subject. Overall means increased (33.5 to 37.0 to 39.0 mm) rather than decreased over the three sessions, but the reverse was true for the subject with the largest mean value in the first session.

The final question concerned the location of the closest approach relative to the obstacle. Differences in both x' and y', the coordinates parallel to and perpendicular to the straight path, were considered separately. With respect to the latter, the closest approach occurred when the tip was already proximal to the entire obstacle. This follows geometrically from the fact that the tip usually passed the obstacle on a diagonal course. With respect to the former, the location of the point of closest approach relative to the proximal end of the obstacle again depended on both the orientation of the movement and the location of the obstacle (Fig. 10). The effect of movement orientation was clearest for obstacles at the centre position: the closest approach occurred before the tip passed

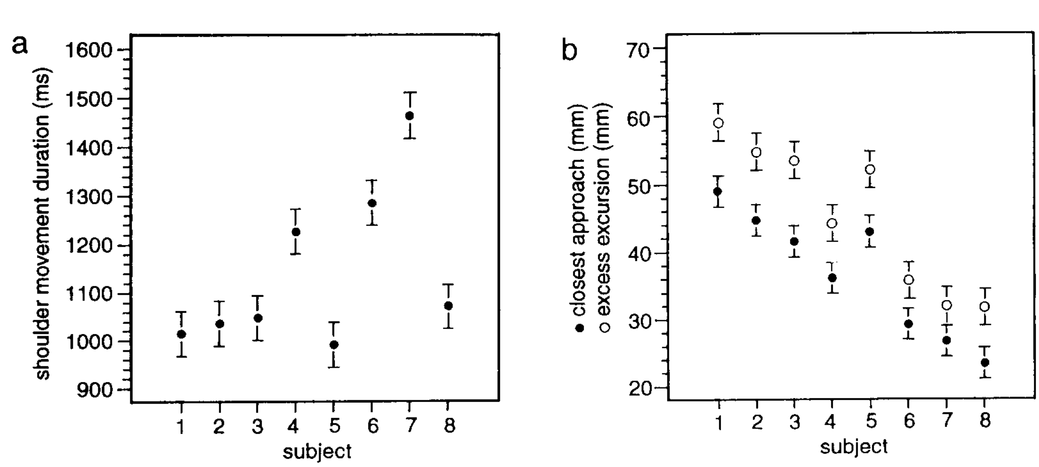

Fig. 9a,b. Subject means for movement duration, path excursion and closest approach to the obstacle. Means and 95% confidence intervals were computed over all obstacles extending at least as far as the straight path. Each mean is based on 149 values

Table 1. Mean change in joint angle as a function of movement orientation

Movement	Change in angle between initial and final positions (degrees)			Number of movements
	Shoulder Mean ± SD	Elbow Mean ± SD	Wrist Mean ± SD	
Long diagonal (I1–T1)	-31.2 ± 13.0	96.5 ± 16.0	-7.1 ± 15.2	288
Short diagonal (I2–T2)	-18.7 ± 9.6	61.4 ± 11.0	-7.3 ± 13.5	384
Far frontal (I3–T3)	50.6 ± 5.0	4.5 ± 6.0	-13.5 ± 10.5	480
Near frontal (I4–T4)	57.8 ± 9.5	6.5 ± 9.4	-16.3 ± 12.1	336

Positive values correspond to joint flexion

the obstacle in frontal movements (mean difference $x' = -8.0 \pm 8.1$ mm, $n = 240$) and after the tip passed the obstacle in diagonal movements (mean difference $x' = 4.7 \pm 11.8$ mm, $n = 200$). For asymmetrical positions of the obstacle, the point of closest approach was more in the direction of the start for obstacles at position 1 (25% and 33%) and, for frontal movements, more in the direction of the target for position 3 (67%). Thus, for frontal movements, the relationship for obstacles at the centre position was more like that for position 1; for diagonal movements, it was more like that for position 3. Differences among the subjects in the relative position of the point of the closest approach were highly significant ($P < 0.001$), but six of the eight formed a homogeneous group. The two extreme subject means were -7.5 ± 15.0 mm, for the subject showing the greatest variance and the largest change with obstacle position, and $+0.69 \pm 14.0$ mm ($n = 149$ for each subject).

In summary, the analysis of paths showed that several features were changed when the movement task was rotated in the workspace (comparison of frontal and diagonal movements) or translated (comparison of the two frontal movements). These included the minimum distance, its location relative to the obstacle, and the size and location of the maximum excursion from the straight path.

General characteristics of joint movements used in avoiding obstacles

When obstacles induce path changes, joint movements necessarily change too. The analysis focused on the nature of these changes and on the use of the wrist in particular. In the absence of obstacles, shoulder movement usually was unidirectional (Fig. 2). Elbow movement was unidirectional for diagonal movements but generally involved flexion and extension for frontal movements. Net movement of the shoulder was larger for frontal movements; that of the elbow was larger for diagonal movements (Table 1). The net movement of the wrist was much smaller than that of both shoulder and elbow (Table 1).

In the presence of obstacles, the movement of all three joints became more complex with larger excursions and one or more reversals in direction. These changes were analysed in terms of three parameters: (1) as a quantitative measure of movement complexity, the number of reversals in direction; (2) as an absolute measure of extra joint movement, the size of the largest excursion from the direct line between initial and final angles; and (3) as a relative measure of extra joint movement, an index relating both number and size of such excursions to the net movement. To calculate the index, the total travel was determined by summing the absolute values of the changes in going from initial to final angles via the extreme angles of any excursions. Then the absolute value of the net change in angle was subtracted from the total travel and the result divided by the total travel to obtain the index. Thus, the index varies from 0, for a unidirectional movement, to 1, for a movement with joint excursions which are very large relative to the net change.

Since the net change in angle is part of the index, it was necessary to examine whether the initial and final angles were affected by the presence of obstacles. The initial and final angles and thus the net change necessarily vary with the position of the pointer in workspace, so movement orientation was included in the analysis of variance. Shoulder angles adopted at the start and end did not vary measurably with the presence or absence of an obstacle or with obstacle length. Neither did initial elbow and wrist angles vary except for the trivial case of long obstacles near the starting point of diagonal movements which conflicted with the normal configuration assumed by some subjects. For all subjects, the wrist was almost straight at the starting positions. Seven of the eight subjects began with the wrist slightly extended (means between -10 and 0°); the eighth began with the wrist slightly flexed (mean 14°).

Final angles for both elbow and wrist did differ significantly in the presence of an obstacle. Elbow flexion at the final position was about 2° larger for obstacles at positions 2 and 3 than values for no obstacle or obstacles at position 1. Net wrist movement from start to target was in the direction of more extension; final wrist angles ranged from -34 to 0°. In the presence of an obstacle, the wrist was about 4° more extended at the final position. This dependence was the counterpart of the elbow change noted above. It reflected increased extension for obstacles at positions 2 and 3 compared with no obstacle or those at position 1. Thus, net joint changes at the elbow and wrist did depend on the presence of an obstacle to a slight degree, but the changes were much less than the obstacle-induced excursions described below. Moreover, the changes were such that any increase in the index arising from obstacles would be underestimated rather than overestimated.

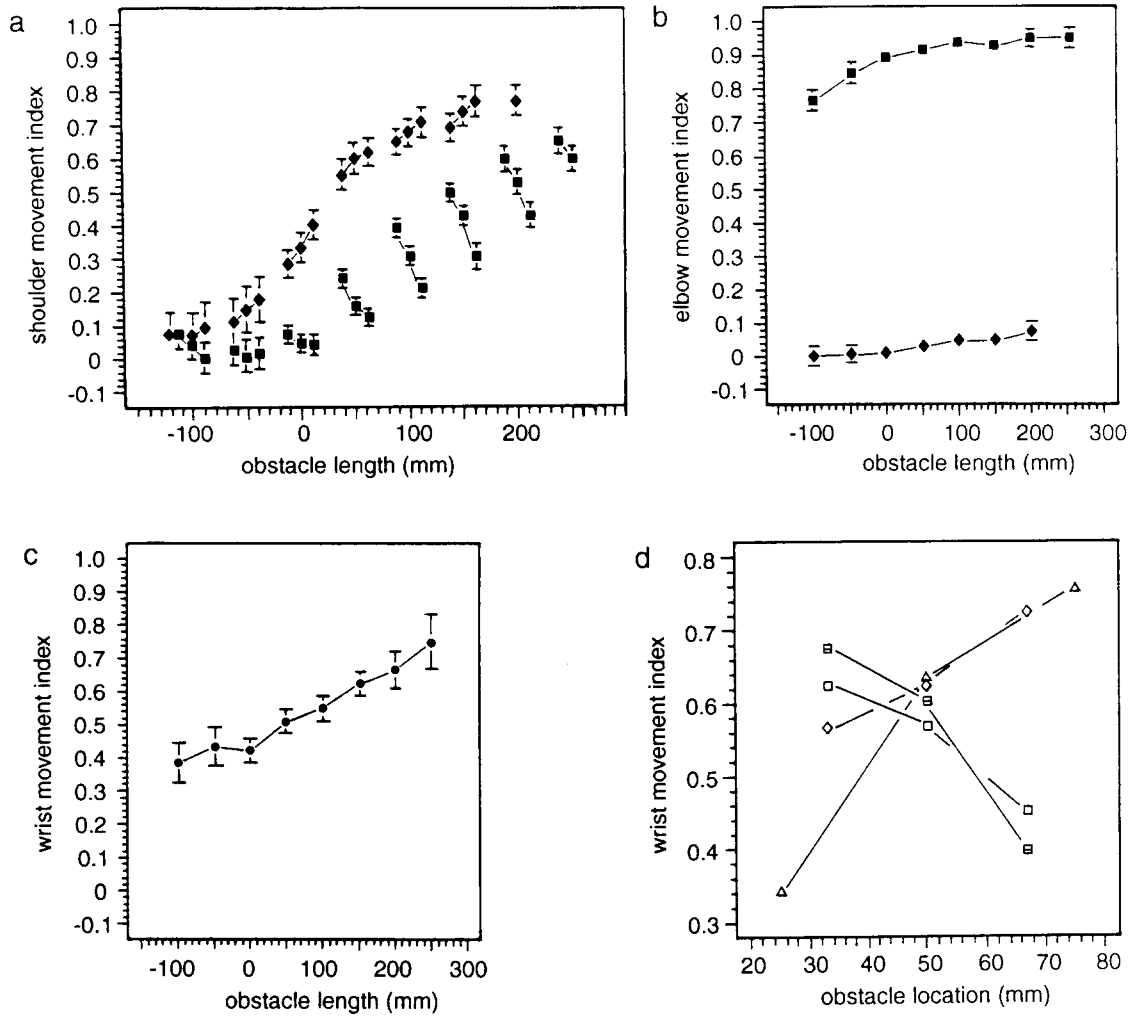

Fig. 11a–d. Dependence of the joint movement index, a measure of excess joint excursion, on obstacle length. As explained in the text, the index varies from 0 for joint movements along a direct path between initial and final angles to 1 for movements in which total joint excursions are large relative to the net change in angle. For shoulder (**a**) and elbow (**b**), means for diagonal (◆) and frontal (■) movements differ significantly. For the shoulder, the *three connected means* at each obstacle length represent the means for obstacles at positions 1–3. For the wrist, the means also increase monotonically with obstacle length (**c**), and there was a highly significant interaction ($P < 0.0001$) between obstacle location and movement orientation (**d**). For frontal movements (□,⊟), wrist indices were larger for obstacles near the start than for those near the target. For diagonal movements (△,◇), the reverse was true. In order to compare similar obstacle lengths for all movement orientations, only obstacle lengths of between 100 and 155 mm are included in **d**. Numbers of values in **d** range from 24 to 48

Changes in shoulder movement in avoiding obstacles

For the shoulder, the most common movement profile (80% of all cases) in the absence of an obstacle contained no reversals or large deviations from the almost straight, sigmoid curve from initial to final angles. For most obstacles proximal to the straight path, geometrical constraints force shoulder movement to be more complex. The most common profile was biphasic with a single, large deviation from the straight trajectory and a reversal in direction occurring in the middle half of the movement (e.g. Fig. 2). Additional reversals, either in the form of corrections near the end of the movement or a short excursion and reversal in the initial part of the movement, were infrequent.

The decrease in unidirectional movements and increase in complexity were reflected in the movement index. For the shoulder, as for all three joints, the correlation between movement index and obstacle length was positive and significant. Of all three indices, the index for the shoulder showed the clearest and most linear dependence, varying from near zero for obstacles outside the straight path to near 0.8 for the longest obstacles (Fig. 11a). The slope of the increase was steeper for the diagonal movements than for the frontal movements. Moreover, there was a significant interaction between the location of the obstacle and the orientation of the movement. The movement index increased faster for obstacles nearer the start in frontal movements and faster for those nearer the target in diagonal movements (Fig. 11a).

The absolute changes in shoulder motion were also relatively simple and uniform. The angle at the largest deviation from the straight trajectory was more negative than the corresponding angle obtained by interpolating linearly between initial and final angles, i.e. the upper arm was rotated more to the rear. The size of this excess excursion increased linearly with the length of the obstacle. Correlation coefficients and slopes were similar for all four movements. In accord with the changes in the movement index, the primary excursion in frontal movements was more negative, i.e. larger, as the obstacle location shifted from the target towards the start. For diagonal movements, the reverse was true. For frontal movements, the maximum excursion at the shoulder generally preceded the maximum excursion in the path: 99% of the temporal differences were negative and the mean and medians were -206 ms and -192 ms, respectively. For diagonal movements, in contrast, the maximum excursion followed the maximum excursion in the path: 90% of the temporal differences were positive and the mean and median were 97 ms and 88 ms, respectively.

Changes in elbow movement in avoiding obstacles

The patterns for the elbow were similar to those of the shoulder in that joint reversals became more frequent and excursions larger as obstacle length increased. However, as in unobstructed movements, joint excursions varied considerably according to the orientation of the movement. For frontal movements, a biphasic profile with a single reversal in joint movement was the most common type, both with and without obstacles. For diagonal movements, in contrast, all of the unobstructed movements were unidirectional. The presence of an obstacle increased the frequency of single reversals, especially for the 40–cm diagonal path, and this increase was correlated with obstacle length. However, unidirectional movements remained the most common type. Movements with more than one change in direction were more common than in the shoulder but still amounted to only 10% for the movement where they were most frequent, the proximal frontal movement.

Besides showing the same qualitative pattern for movement orientation, the movement index revealed a quantitative increase in movement complexity with obstacle length. It varied between 0.75 and 0.95 for frontal movements and between 0.0 and 0.1 for diagonal movements (Fig. 11b). The location of the obstacle was a significant factor only for the diagonal movements: obstacles near the target elicited movements with larger indices than those at the middle position or near the start.

As reflected in the index, the size of the excess joint excursions at the elbow varied more systematically for frontal movements (Fig. 12b). For these movements, all turning points were positive (i.e. more flexed) relative to the simple sigmoid curve between initial and final angles and they increased with obstacle length. For diagonal movements, deviations from this curve were infrequent (152 of 616 recorded movements) and, when present, variable and small (means of 15–26° for different classes of obstacle lengths). For frontal movements, elbow excursion did not vary with obstacle position; for diagonal movements, it was larger for obstacles at either of the eccentric positions than for those at the centre position.

For diagonal movements, the maximum excursion at the elbow, like that at the shoulder, generally occurred after the furthest excursion in the path for diagonal movements: 90% of the temporal differences were positive and the mean and median were 274 ms and 266 ms, respectively. For frontal movements, the maximum occurred near the maximum excursion in the path (mean -13 ms, median -17 ms, $n = 755$) and the standard deviation was smaller than that for the frontal movements.

Changes in wrist movement in avoiding obstacles

Wrist movements usually contained one or more changes in direction. For movements with no obstruction, this was in part because the wrist moved little, so small fluctuations and any final corrections were more prominent in the data plots for the wrist than for the other two joints. Both with and without obstacles, movements with three changes in direction were most frequent. Again there was a difference depending on the orientation of the movement: the second most common pattern contained one reversal for frontal movements and two reversals for the long diagonal. As obstacle length increased, the number of movements with no reversals decreased, the number with one reversal increased for the short diagonal movement and the number with three excursions increased for frontal movements. Whenever just two reversals were present, one was typically a large excursion in the middle of the movement and the second was usually a smaller excursion in the last quarter of the movement.

The change in the movement index for the wrist was intermediate to those for the shoulder and elbow and the variation was greater (Fig. 11c). The mean index increased from 0.3 to 0.7 as obstacle length, the major influence, increased. The orientation of the movement had a small but significant effect ($P < 0.001$). The location of the obstacle was significant only in its interaction with movement orientation (e.g. Fig. 11d): as the obstacle moved towards the target, the index increased for frontal movements and decreased for diagonal movements.

The presence of an obstacle elicited absolute changes in wrist motion which were more apparent in the amplitude of wrist movement than in the number of reversals. Whereas, in the absence of obstacles, wrist excursions were generally limited to $\pm 15°$, in the presence of obstacles of 100 mm or more, larger excursions in either direction were the rule (Fig. 13). Two different strategies were evident. Overall, for small obstacles, the main excursion tended to be small and negative, i.e. the hand extended and the pointer tip trailed the hand in passing the obstacle. For longer obstacles, the main excursion from the interpolated line tended to be large and positive, i.e. the hand flexed in the direction of motion and the pointer led the hand in passing the obstacle. This transition occurred at shorter obstacle lengths for the diagonal movements; wrist extension for small obstacles was less pronounced for the short diagonal movement (Fig. 12c). For diagonal movements, the size of the positive excursions (wrist flexion) increased as the obstacle shifted towards the target; for frontal movements, the reverse was true (Fig. 12d).

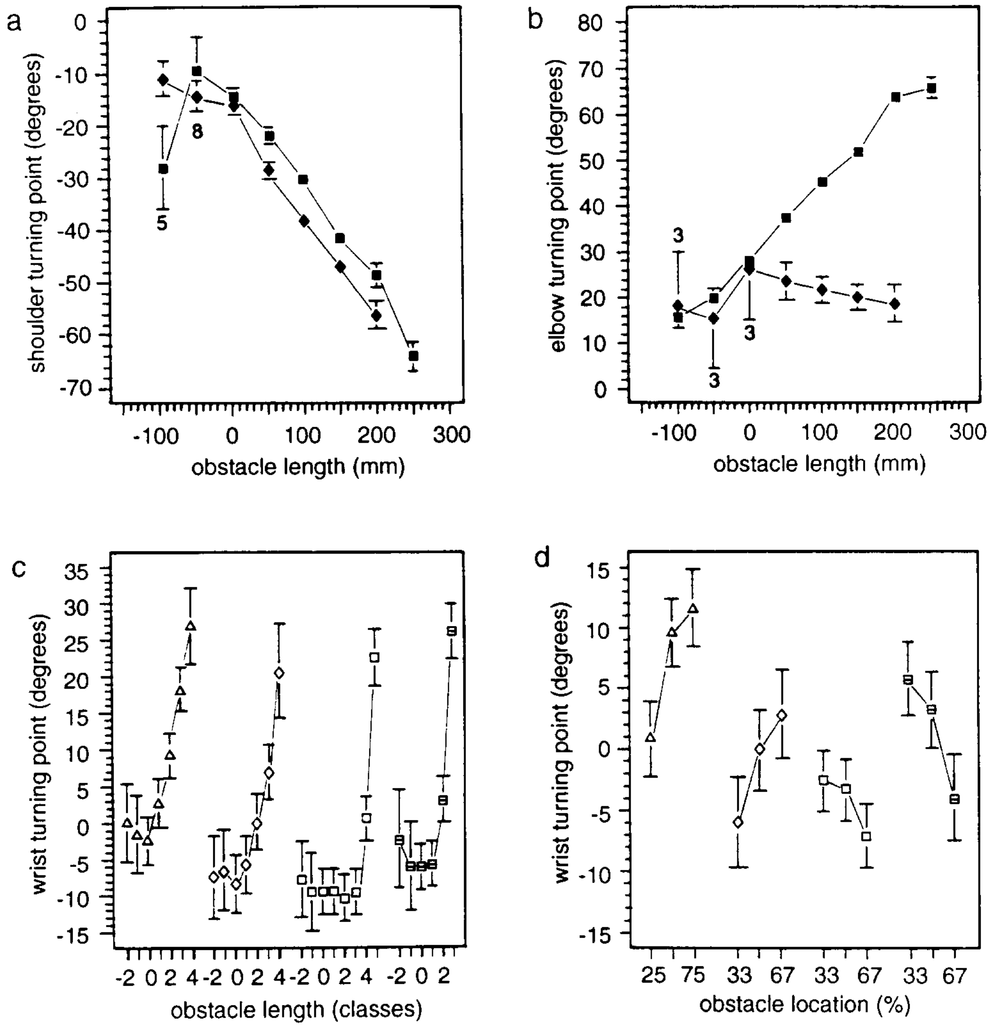

Fig. 12a–d. Dependence of the excess joint excursion on obstacle length. Joint excursion is measured as the difference between the angle at the most extreme turning point and the corresponding angle obtained from a linear interpolation between initial and final angles. For the shoulder (**a**), excess extension (negative angles) increases with obstacle length for both frontal (■) and diagonal (◆) movements. For the elbow (**b**), excess flexion (positive angles) increases for frontal movements but not for diagonal movements. Except where otherwise indicated (*numbers near error bars*), the number of values in the means ranges from 22 to 142. **c** The dependence of wrist excursion on obstacle length differs significantly among the four movements, so these are plotted separately. For obstacles ending distal to the straight path (negative length classes), wrist excursions are predominantly small extensions (negative ordinate values). With increasing obstacle length, means shift towards large wrist flexions and the transition occurs at shorter obstacle lengths for diagonal movements (△,◇). **d** Wrist excursions also depend on obstacle location. As the obstacle moves towards the target, means shift towards flexion for diagonal movements (△,◇) and towards extension for frontal movements (⊟,□)

The timing of the primary turning point relative to the furthest excursion in the path also varied with movement orientation. For diagonal movements, the distribution of temporal differences was monophasic, centered at a mean of 99 mm ($n = 573$). For large obstacles, flexion at this time moved the pointer rapidly past the obstacle. For frontal movements, the distribution ($n = 726$) was biphasic, with one peak between -200 and -100 ms and another between 100 and 200 ms.

Secondary wrist excursions which followed the largest excursion, those occurring between 300 and 700 ms after the maximum excursion in the path, were usually negative relative to the straight trajectory, i.e. they represented extra wrist extension. These secondary extensions became more negative with increasing obstacle length. They also depended on movement orientation. The mean size of these deviations was more negative for frontal movements ($-6.2 \pm 6.3°$, $n = 447$) than for diagonal movements ($-0.8 \pm 4.6°$, $n = 441$). They did not depend on obstacle location. Functionally, this wrist extension and the subsequent flexion bringing the wrist to its final angle corresponded to the preferred direction of approach by the pointer tip to the target.

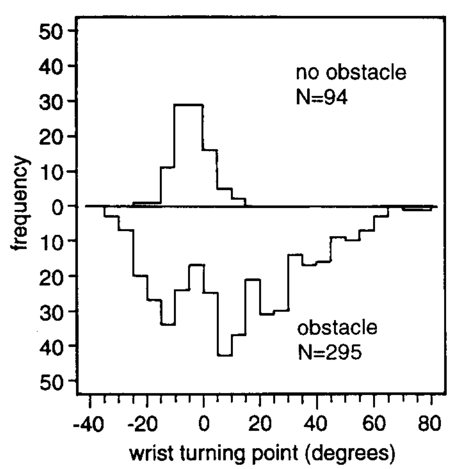

Fig. 13. Distributions of joint excursions at the wrist for movements with no obstacle and for those with large obstacles. The figure plots number of occurrences versus maximum joint excursion. Positive and negative values on the abscissa correspond, respectively, to excess flexion and extension at the wrist relative to the straight path between initial and final angles. In the absence of an obstacle (*upper histogram*), wrist excursions are small; in the presence of an obstacle equal to or greater than 120 mm (*lower histogram*), large excursions in either direction are more common

Reversals in the initial part of the movement (600–200 ms before the furthest excursion in the path) were also small and negative. These reversals occurred when wrist flexion was preceded by wrist extension as the movement began, i.e. the hand initially rotated opposite to the direction of pointer motion. These reversals occurred before the nearest approach to the obstacle. Qualitatively, this sequence of wrist movements kept the pointer tip on a straight or gently curved path towards a point near the proximal end of the obstacle. The initial extension helped compensate for the concurrent elbow flexion until shoulder extension retracted the elbow far enough that elbow flexion no longer carried the hand directly at the obstacle. The size of these excursions was significantly correlated with the length of the obstacle and depended on movement orientation. Overall means for the longer diagonal movement were significantly more negative ($-2.8 \pm 4.5°$, $n = 130$) than those for the shorter diagonal (-1.4 ± 3.3, $n = 210$), which, in turn, were more negative than those for the two frontal movements separately or together ($-0.5 \pm 4.0°$, $n = 342$). The dependence on obstacle location was not significant; differences in the means were less than 2°. Differences among different subjects were significant; within subject means ranged from -0.71 to $-5.0°$.

The durations of the movements as a whole and the relative timing of joint movement and joint reversals also were affected by obstacle length and location. For example, the duration of the shoulder movement increased almost linearly with the length of the obstacle. A detailed consideration of these parameters will be presented elsewhere together with a discussion of the kinematics.

Discussion

The results presented above provide several insights into strategies used by humans to control the redundant degrees of freedom available in the arm. In the robotics literature, redundancy is often discussed in relation to obstacle avoidance, but this aspect of arm control has not been well studied. Investigations of multi-joint control in humans have usually considered movements using two joints, the shoulder and elbow. Results for this non-redundant case, using two joints to make movements in a plane while avoiding simple obstacles, can be summarized in the following way. As a rule, human subjects follow a smoothed version of the shortest, straight-line path. Actual paths usually contain more or less straight segments leading to and from the vicinity of the obstacle and connected by a segment of greater curvature. However, more rounded paths with nearly constant curvature also occur. Whatever the exact form, paths used in avoiding obstacles are similar to those used in making comfortable target movements via a specified intermediate point, a via point. Hence, it is assumed that path planning incorporates an intermediate point in the neighbourhood of the obstacle (Abend et al. 1982; Flash and Hogan 1985). Together, the decrease in tangential velocity and the increased curvature near the obstacle have been interpreted as evidence for segmentation of the movement into two separately planned subunits (Abend et al. 1982; see also Viviani and Terzuolo 1982). However, these features also follow from the application of various optimization criteria to determine a complete path constrained to pass through the via point. Good agreement with experimental data for two-joint movements has been demonstrated for algorithms based on minimizing the square of the jerk (Hogan 1984; Flash and Hogan 1985) or the square of the rate of torque change (Uno et al. 1989; but see Flash 1990 for a critique).

These control algorithms can be extended to the redundant case. In fact, one interesting feature of the minimum jerk hypothesis is the prediction that the path should be unchanged (Flash and Hogan 1985). Because this criterion only applies to the tip trajectory, the orientation of the movement in the workspace and the number of joints used in making the movement are irrelevant. In support of this claim, Flash and Hogan (1985) cite findings of Abend et al. (1982) and their own qualitative experiments to the effect that hand paths do not change when the wrist is free to move.

In contrast to the experimental studies mentioned above, which established the general similarity between obstacle avoidance and movements through via points (Abend et al. 1982) and then considered theories for deriving complete trajectories incorporating a via point (Flash and Hogan 1985), the present report focuses on a quantitative description of the paths taken and the use of redundant degrees of freedom. The corresponding model of path planning is presented elsewhere (Brüwer and Dean, in preparation).

Path planning

With respect to path planning, the systematic investigation of different obstacle locations and lengths revealed several planning criteria. Moreover, it showed that the invariance predicted by the minimum jerk hypothesis does not strictly hold: paths are qualitatively similar but not quantitatively invariant for different positions and orientations in the workspace. Four points are worth noting.

First, the paths followed by the pointer tip are qualitatively similar to those reported for arm movements using two joints (Brüwer and Dean, in preparation). Moreover, the minimum distance from the obstacle is remarkably constant for obstacles of different lengths and locations and for different orientations of the path in the workspace (Fig. 7), suggesting that minimum distance is one parameter used in planning. In analogy with previous investigations (Morasso 1981; Hogan 1988), such invariances when paths are described in workspace coordinates support the hypothesis that planning is carried out in terms of hand or workspace coordinates, as argued by Bernstein (1967), rather than joint coordinates.

Second, one might expect that the closest approach would be more or less constant, because it is so immediately related to the task of avoiding the obstacle. This was not the case (Fig. 7). Moreover, the closest approach varied from one subject to another in a way that suggests a trade-off between shortening movement duration and reducing the amount of extra excursion by passing closer to the obstacle (Fig. 9). This inverse relation between speed and accuracy is also true of simple, unobstructed pointing (Fitts 1954).

More important, the closest approach varied systematically with obstacle position and with movement orientation. Comparing values for the two frontal movements (Fig. 7), it appears that the closest approach – and the excess excursion as well (Fig. 5) – depends on the distance of the obstacle from the shoulder or body, a workspace parameter related to the body, rather than the required excursion from the straight-line path, a workspace parameter related to the task. This interpretation is supported by the absence of a decline in the closest approach for diagonal movements, where the distance between the proximal end of the obstacle and the shoulder changes less. Both comparisons point to inhomogeneities in the workspace. One such inhomogeneity relates to postural costs or comfort. More proximal paths are associated with increased flexion and therefore, according to the cost function description, increased costs at the elbow and wrist. Another relates to the geometry of the different actions of the joints in the workspace. The closest approach is smaller for small obstacles in diagonal movements, where the functional redundancy is reduced because the elbow can contribute less to moving the pointer away from the straight path. (At both initial and final positions, the orientation of the lower arm is such that elbow movement carries the hand almost parallel to the path and does not help move hand and pointer proximal to the obstacle.) Both systematic changes indicate that the approach distance is just one variable among several factors considered in planning a path.

Third, if path planning only involves the kinematics of the tip trajectory, as in the minimum jerk hypothesis, then paths should be invariant with respect to translation or rotation in workspace. The two systematic changes in the closest approach just mentioned already indicate that this is not strictly true. Movement orientation also influenced the location of the turning point or furthest excursion from the straight path (Figs. 5,6). Such differences could be reconciled with the minimum jerk hypothesis or other kinematic criteria defined for the end-effector on the assumption that the path planner generates an invariant trajectory which then suffers distortion through inertial and visco-elastic interactions during execution (Flash and Hogan 1985; Hogan 1988). The same mechanical factors can generate the small hooks often seen at the end of certain paths (Flash and Hogan 1985; Flash 1987). We do not think that these dynamic factors can provide a complete explanation for the large changes found here and elsewhere (Brüwer and Dean, in preparation). We do not think that the dynamic factors in our experiments were significantly different from those in other studies. Certainly the durations of the movements studied here were not greatly different from those reported in the literature (e.g. 20- to 40-cm movements in 800–1500 ms in Abend et al. 1982, or 400–1000 ms in Flash and Hogan 1985), even allowing for the longer movements. Path differences depending upon location in the workspace are an intrinsic feature of control models which consider parameters other than the kinematics of the end-effector. Planning to minimize torque change is one example (Uno et al. 1989). Thus, we interpret our findings as reflecting an influence of joint-space parameters on path planning.

Our results do agree with two predictions of the minimum jerk hypothesis regarding eccentric obstacles: (1) the furthest excursion should be on the side of the obstacle towards the midpoint of the straight path, and (2) the closest approach should be on the opposite side, away from the midpoint. Both tendencies are present in the results (Figs. 6,10).

Fourth, as already mentioned, experimental evidence indicates that obstacle avoidance involves introducing via points into path planning (Abend et al. 1982; Flash and Hogan 1985). If this is so, the question arises as to how via points are specified. The point of closest approach is intuitively a good candidate, but it is not the only one. Where distinct changes in curvature suggest a segmentation of the movement, it would be logical, although not strictly necessary, to identify the via point with the break between segments, as has been done in some models (Flash and Hogan 1985). For the obstacles studied here, these two points would be the same if the segmentation occurred somewhere on the line through the proximal end of the obstacle and perpendicular to the straight path. This was not the rule in our experiments. Besides the two tendencies for eccentric obstacles mentioned in the previous paragraph, there is a tendency for the turning point to occur after the pointer tip passes the obstacle. The latter is particularly evident in the right-to-left frontal movements studied here. Overshooting of this kind can occur in the minimum jerk model, so the results do not identify the via point.

Overshooting could also represent a second strategy for obstacle avoidance under visual control, one that in addition to specifying the point of closest approach also prefers to let the turn towards the next target only occur after the pointer tip passes the obstacle. For the frontal movements, this can be achieved by delaying the reversal in elbow motion, a tactic which is not applicable to the diagonal movements. However, in left-to-right movements in a frontal plane (Brüwer and Dean, in preparation), the maximum excursion was also to the left of the obstacle, i.e. before the tip passed the obstacle, so this asymmetry again reflects inhomogeneities in the workspace.

Geometrical constraints on arm configurations used in avoiding obstacles

The discussion of path characteristics has shown that path parameters vary with location in ways that indicate inhomogeneities in the workspace and suggest that these are related to the actions of the joints. Viewed another way, the effective number of degrees of freedom varies within the workspace.

The shoulder and elbow both have greater freedom of movement than the wrist and, due to their longer lever arms, a given change in angle produces a larger movement of the pointer. Moreover, even if the wrist could rotate beyond 90°, shoulder and elbow must still move in such a way that the wrist itself passes proximal to the obstacle. This non-redundant problem with respect to the wrist must be solved at the same time that the redundant problem is solved for the pointer tip. Hence, the two proximal joints play the primary role in avoiding obstacles. Simply moving the wrist past the obstacle may compel shoulder and elbow to include direction reversals and to change the relative timing of their movements. A similar geometrical constraint applies to the shoulder alone: because wrist movement can only vary the effective length of the lower arm and pointer to a limited extent, even relatively small obstacles compel the shoulder to make biphasic movements in order to move the elbow sufficiently far from the obstacle. In the experiments reported here, the geometrical constraints are relatively simple. For all but very small obstructions in the normal path, the shoulder must rotate backward in order for the hand to avoid the obstacle. For frontal movements, elbow flexion can shorten the length of the distal segments and thereby reduce the required amount of shoulder excursion. For diagonal movements, the elbow cannot play this role effectively because its action moves the hand more or less parallel to the straight path. As a result, shoulder excursions are larger.

Control of redundant degrees of freedom and use of the wrist

One central question for the present investigation was whether the additional degree of freedom available at the wrist was actually used in moving past obstacles. Measurements of wrist movement have not previously been reported. In unobstructed movements, the wrist generally was not used much. Movements which did occur could be explained by the influence of static cost functions and by wrist involvement in final corrective movements at the target.

Joint movements necessarily become more complex in the presence of obstructions. In the situations studied here, the subjects theoretically could have avoided the obstacles solely by adjusting the joint excursions of shoulder and elbow, i.e. the pointer tip could be moved proximal to the obstacle while keeping the wrist fully extended. Even the longest obstacles would not have forced shoulder and elbow to their mechanical limits. In fact, the subjects chose to flex the wrist (Fig. 12) and thereby reduce the amount of shoulder extension (see also Brüwer and Dean, in preparation). Moreover, the extra excursion of the wrist increased systematically with increasing intrusion of the obstacle into the straight path. This result shows that the extra degree of freedom is used in moving past obstacles and that it is incorporated in a regular manner into all movements, not just when the shoulder and elbow reach the limits of their range and there is no geometrical alternative.

When there are redundant degrees of freedom, there must be a way of distributing the required motion among the several joints. The solution used for static arm configurations can be described by assigning theoretical costs which are U-shaped functions of joint position and then selecting a configuration to minimize the sum of the costs at the three joints (Cruse 1986; Cruse et al. 1990).

These costs associated with static joint angles also appear to influence movement. When avoiding an obstacle forces the wrist to move away from its most comfortable position, the total cost of the arm configuration rises. The increase depends on the size of the obstacle and the excursion it requires as well as on the location in the workspace. Subjects apparently try to limit these costs by restricting the amount of excess joint excursion, but to do so they must accept a closer approach to the obstacle, as described above. For frontal movements, the linear decrease in the latter (Fig. 7) argues against this decrease being due simply to geometrical limits, i.e. limits to joint excursion which prevent the arm from maintaining the normal distance. Thus, joint movements involving excess excursions and direction reversals also represent costs which are balanced against the acceptable minimum distance from an obstacle.

The use of the wrist suggests but does not prove active use of this additional degree of freedom in avoiding obstacles. Alternatively, the arm configuration assumed at each point along the path might simply be that specified by the static cost functions. For example, if the obstruction forces the subject to move the pointer through a point close to the chest, the arm configuration specified by the static cost functions may include wrist flexion. Two features of the present results suggest that the degree of freedom at the wrist is actively and explicitly incorporated into avoiding obstacles. First, qualitatively and quantitatively, the linear increase in wrist excursion with obstacle length represents a larger response to small changes in tip position than that inherent in the typical U-shaped cost functions measured for wrist angles. In particular, the static minimum cost configurations do not show such a sharp transition between extension and flexion (Fig. 12). Second, the complexity of the wrist movements for some obstacles, e.g. when the wrist is first extended to move the hand away from a nearby obstacle and then flexed to fold the hand proximal to the obstacle, implies an active role. The initial extension, in particular, is a change in wrist angle that would not be expected on the basis of either the static cost functions (Cruse 1986) or the augmented control model applied to simple pointing movements (Cruse and Brüwer 1987). This can be demonstrated by a direct comparison of configurations assumed in moving past obstacles with those specified by the minimum cost principle for each point in the same path (Fig. 14). This principle leads to fairly monotonic flexion of the wrist for the smaller obstacles and movements tested here and to flexion and extension for larger obstacles.

The small corrective movements near the target, the "little hooks", would also not be predicted by the static cost function model, but they are better explained as discrete corrective movements under the conditions of visual feedback used here. Little hooks can also result from inertial and visco-elastic interactions in executing a minimum jerk trajectory (Flash and Hogan 1985), but the examples from these simulations appear qualitatively different from the large, final corrections occasionally seen

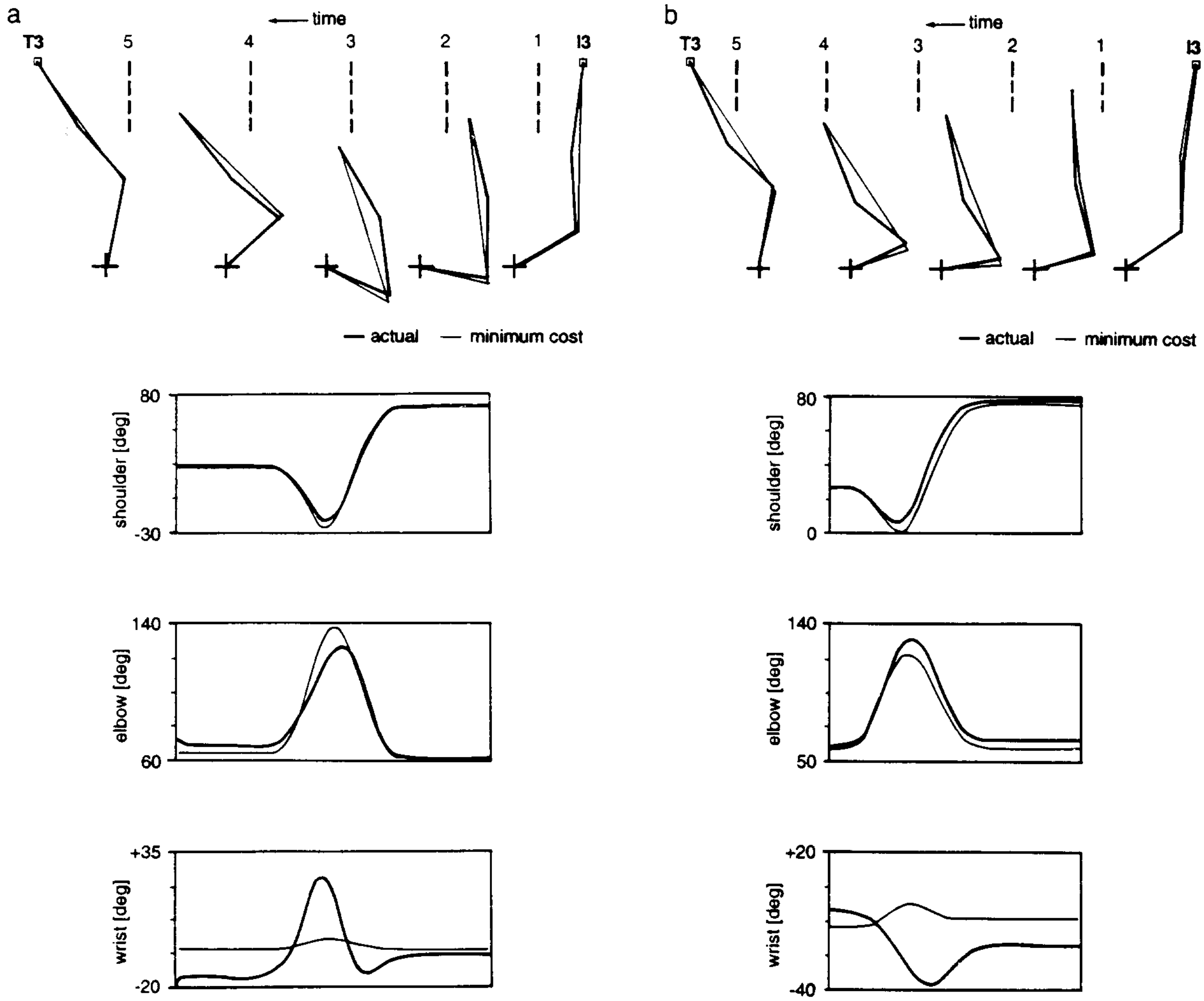

Fig. 14a,b. Comparison of actual joint movements with those predicted by the static cost functions. The *upper panel* compares, for selected points in the movement, the arm configuration actually measured (*thick line*) with that predicted by the minimum cost principle using the cost functions measured under static conditions (*thin line*). In order to preserve the proper direction of movement, time in the sequences proceeds from *right to left*. The *lower panel* shows the complete joint movements. **a** An example where the predicted wrist movement is smaller than but in the same direction as that actually measured. **b** An example in which the wrist moves opposite to the predicted direction, extending rather than flexing

in the present experiments. Use of the wrist for fast corrections under visual control may also be used to avoid colliding with the obstacle, as in the early extension described above or the flexion in moving past large obstacles, i.e. it could correct for variation in shoulder and elbow movement. However, this role cannot account for all the wrist movements. It would not explain why shoulder and elbow errors and the resulting need for correction should increase with obstacle length. Furthermore, a direct comparison of movements using two and three joints (Brüwer and Dean, in preparation) and the use of the wrist in short, fast pointing movements (Dean and Brüwer 1993) both show that wrist movements are actively incorporated into the synergy.

According to the minimum cost principle for stationary arm postures (Cruse 1986; Cruse et al. 1990), the initial and final joint angles should not vary with the presence of an obstacle except in the trivial case that an adjustment is necessary to avoid resting the arm or pointer on the obstacle. This was true for the initial position, as could be expected because obstacles only appeared after the pointer was moved to this position and the subjects did not readjust the arm configuration. Having to avoid an obstacle, however, did cause a small change in final joint angles at the target. For short obstacles, this represented a kind of hysteresis in which the final wrist angle was biased in the direction of the extension performed in passing the obstacle. However, these changes in elbow and wrist angles were only a few degrees, so previous arm configurations and any dynamic aspects of the movement to the target do not have a strong influence. A subjective need to increase the distance of hand and lower arm from the obstacle or to maintain clear visibility of the workspace may also have contributed to the increased elbow flexion and wrist extension at the target.

In summary, the results show that human subjects employ the redundant degree of freedom added by the wrist in a systematic way when avoiding obstacles. It is used both to move the hand away from the obstacle while shoulder and elbow start to move the wrist itself around the obstacle, it is used to move the pointer rapidly past the obstacle, and it is used to shorten the effective length of the distal limb and thus reduce the amount of joint excursion required from the proximal joints. With respect to path planning, the results indicate that the minimum distance from the obstacle is one variable in path selection and they show that small reductions in the minimum distance are accepted as the amount of extra joint movement compelled by the obstacle increases. This finding, together with the observation that paths differ depending on movement orientation, suggests strongly that path planning does not use workspace coordinates alone but rather a mixture of workspace and joint-space parameters.

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