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Geometric features of workspace and joint-space paths of 3D reaching movements

Mary D. Klein Breteler [a,*], Ruud G.J. Meulenbroek [a], Stan C.A.M. Gielen [b]

[a] *Department of Experimental Psychology, University of Nijmegen, Nijmegen, The Netherlands*
[b] *Department of Medical Physics and Biophysics, University of Nijmegen, Nijmegen, The Netherlands*

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Abstract

The present study focuses on geometric features of workspace and joint-space paths of three-dimensional reaching movements. Twelve subjects repeatedly performed a three-segment, triangular-shaped movement pattern in an approximately 60° tilted horizontal plane. Task variables elicited movement patterns that varied in position, rotational direction and speed. Trunk, arm, hand and finger-tip movements were recorded by means of a 3D motion-tracking system. Angular excursions of the shoulder and elbow joints were extracted from position data. Analyses of the shape of 3D workspace and joint-space paths focused on the extent to which the submovements were produced in a plane, and on the curvature of the central parts of the submovements. A systematic tendency to produce movements in a plane was found in addition to an increase of finger-tip path curvature with increasing speed. The findings are discussed in relation to the role of optimization principles in trajectory-formation models. © 1998 Elsevier Science B.V. All rights reserved.

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[*] Corresponding author. Nijmegen Institute for Cognition and Information, P.O. Box 9104, 6500 HE Nijmegen, The Netherlands. Fax: +31 24 3616066; e-mail: kleinbreteler@nici.kun.nl

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1. Introduction

A simple strategy to perform a point-to-point aiming movement is to move along a straight line between starting and target location in the workspace (Morasso, 1981; Flash, 1987). An alternative strategy would be to maintain a constant ratio between the angular velocities of the involved joints during the performance of the movement (Soechting and Lacquaniti, 1981; Rosenbaum et al., 1995; Schillings et al., 1996). The latter strategy corresponds to performing a straight-line movement in joint space which, depending on the joints involved, may result in a curved workspace path. The strategy is assumed to simplify the co-ordination of a multijoint effector system such as, in case of reaching, the arm. Whereas Morasso (1981) and Flash (1987) provided empirical evidence supporting the view that people generally strive towards straight-line movements in workspace in reaching, Atkeson and Hollerbach (1985) found systematic curvature variations for movements in the sagittal plane (see also Lacquaniti et al., 1986). Furthermore, Haggard and Richardson (1996) recently showed that although finger-tip paths of point-to-point aiming movements in the horizontal plane are more or less straight in directions to and from the body, they are systematically curved in left-to-right movement directions. In this context, Schillings et al. (1996) also observed that in aiming movements performed on a horizontal drawing surface, the elbow, wrist, and finger joints tend to rotate in synchrony which, as stated above, will usually result in curved end-effector paths in workspace. Cruse and Brüwer (1987), finally, suggested that the shapes of finger-tip paths of reaching movements reflect a compromise between the tendency of subjects to try to produce simultaneously a straight line in workspace and a straight line in joint space.

Analyses of the path curvature of reaching and drawing movements as mentioned above have suggested that a variety of optimization principles may influence the trajectory-formation process. Examples of these principles are the minimum-jerk principle (Flash and Hogan, 1985), the minimum torque-change principle (Uno et al., 1989), the minimum motor-command-change principle (Kawato, 1992), and the minimum travel-cost principle (Rosenbaum et al., 1995). These optimization principles are thought to affect different motor control processes, i.e., motion planning (Flash and Hogan, 1985; Haggard and Richardson, 1996), movement execution (Flash, 1987), and the visuomotor monitoring of movement execution (De Graaf et al., 1994; Brenner and Smeets, 1995). Moreover, the recent suggestion by Kawato (1996) that optimization principles are simultaneously active at different levels of the motor hierarchy, and thus affect the resulting path curvature of reaching movements in conjunction, complicates matters even further. It is apparent that empirical research aimed at evaluating the role of optimization principles in trajectory formation by means of path-curvature evaluations necessitates the study of movement production at more than a single observational level. Therefore, the present study focuses on trajectory formation in both workspace and in joint space.

Most studies mentioned above involved planar, i.e., two-dimensional, reaching movements (for an exception, see Flanders et al., 1996). In the present study, however, three-dimensional reaching movements are investigated. Subjects were seated at a desk-top and were asked to point as fast and as accurate as possible to two targets that were presented on a frontoparallel screen at a distance of 30 cm. Whereas the starting position of the movements was at table height, the target positions were 45 cm higher, i.e. at shoulder height. Consequently, in each trial, a subject had to lift his/her finger from a horizontal platform, move upward and forward to a frontoparallel screen, touch two targets in a prescribed left-to-right or right-to-left direction, and finally, return to the starting position on the horizontal platform. The task thus elicited a three-segment movement pattern in an approximately 60° tilted horizontal plane. Given that subjects tend to approach a flat surface perpendicularly (Brenner and Smeets, 1995), it was expected that the movements towards the frontoparallel screen and the movements back to the home position have a truly 3D nature and would not be constrained to a plane. However, the movement from the first to the second target, both located on the frontoparallel screen, could be expected to consist of a 2D trajectory even though the subjects were asked not to stay in contact with the screen while producing that submovement. The experimental task allowed us to assess the extent to which subjects tend to produce 2D finger-tip paths under conditions which, in principle, were considered to elicit 3D movements. We hypothesized that such a tendency would reflect a movement strategy by subjects to reduce the complexity of the control of 3D-trajectory formation.

By using three starting positions, one in front of the longitudinal body axis of the subjects, and two at fixed distances of 20 and 40 cm to the right, the workspace location of the three-segment movement pattern was varied. On the basis of the findings of Atkeson and Hollerbach (1985) and Haggard and Richardson (1996), it was expected that as movements became located further away from the midsagittal plane, finger-tip paths would become more curved. Furthermore, the rotational direction of the triangular-shaped three-segment movement pattern was varied by alternating the location of the first and second target to be reached for on the frontoparallel screen such that trajectories were produced either in a clockwise or in a counter-clockwise direction. The alternation of first and second target location was intended to increase the variability of the between-trial movement geometry. Trajectories between identical starting and ending locations, but performed in opposite directions in different trials, were expected to have a different curvature, due to context-dependent variations in starting and ending postures (Rosenbaum et al., 1995; Cruse and Brüwer, 1987).

In addition, a target size manipulation was used to elicit movements of different speeds. It was reasoned that faster movements could be performed by rotating the joints in a similar fashion as in slow movements. However, with increasing speed it was expected that subjects would resort more to a strategy of synchronous joint excursions than to a strategy of producing straight-line movements of the finger tip in workspace. Consequently, due to the non-linear relationship between the curvature of finger-tip paths in workspace and the shape of the joint-space paths, it was expected that finger-tip paths would be more curved as target size, and with it, movement speed, increased.

2. Method

2.1. Subjects

Twelve healthy subjects, six males and six females, participated in the present study. They were all right-handed and had good or near corrected vision. All subjects were students except one (age 43). Mean length was 1.72 m (range: 1.60–1.87 m).

2.2. Task and procedure

Participants were asked to reach repeatedly to a target pair on a frontoparallel screen. The subject was seated in front of a rectangular horizontal platform (100 cm width, 30 cm depth) in which three Light Emitting Diodes (LEDs), with a diameter of 3 mm, were mounted (see Fig. 1). The LEDs were located at the height of the subject's belly button and served as starting positions of their reaching movements. One LED was positioned in front of the longitudinal body axis, one in front of the subject's right shoulder and the third LED 20 cm to the right of the right shoulder. At the front edge of the horizontal platform, at a distance of 30 cm from the subject, a frontoparallel semitransparent screen was placed. On the screen two circular targets were projected at 45 cm above the platform, i.e., at about shoulder height, by means of back-projection using an MP8030 Multimedia Projector. One target was

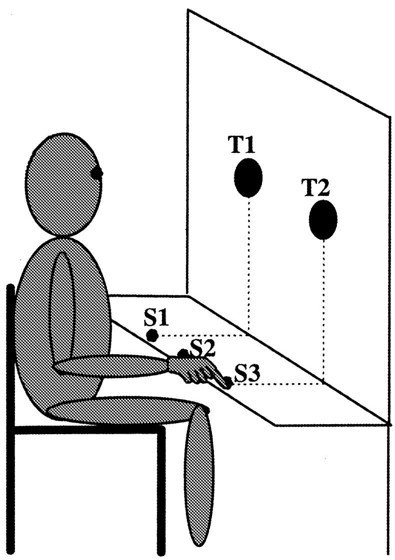

Fig. 1. Experimental set-up. The subject is seated at a table. In the table three LED's are mounted that serve as start positions (S1,S2 and S3). In front of the subject a semitransparent frontoparallel screen is placed on which two targets (T1 and T2) are projected from behind. The dashed lines are only there to indicate that S1 is in front of T1 and S3 is in front of T2; the subject could not see them.

green, the other was yellow. Circular targets with five different diameters were used: 0.6, 1.2, 2.5, 5.0, and 10.0 cm. In each trial the two targets were of identical size. The trial sequence was as follows: first one of the three starting positions on the horizontal platform was lighted and the subject placed his finger on the light. Then the green and yellow target positions were presented simultaneously. After an interval of 1 s an auditory cue indicated to the subject that he/she had to point as fast and as accurately as possible, first to the green target, then to the yellow target and, finally, back to the starting position. Trials in which wrong responses were given, were repeated immediately. The movement from the starting position to the screen and the movement from the screen back to the starting position were unconstrained. The movement from the first to the second target, however, was assumed to be constrained because of the presence of the screen. The screen itself served as an obstacle limiting the volume of the reachable workspace.

The 3D-position of the arm was sampled at a rate of 100 Hz by means of an Optotrak 3020 motion tracking system (spatial accuracy in X, Y and Z directions better than 0.2 mm). Positions of 17 Infrared Emitting Diodes (IREDs) were recorded. Single IREDs were placed on the tip of the right index finger and on the acromioclavicular fissura to measure the positions of the finger-tip and the shoulder. IREDs on rigid bodies near the wrist, elbow and backbone, were used to record arm movements. For measuring the location of the wrist, a PVC-plate, on which three IREDs were attached, was strapped to the forearm near the wrist. Beforehand the approximate location of the wrist joint with reference to the three rigid body IREDs was defined, which made it possible to calculate the position of the wrist joint from the three IREDs. For the elbow a cuff with six rigid-body IREDs attached to it was constructed with hinges on the side at the height of the elbow joint. The cuff was tightly attached to the upper arm with two Velcro strips (above and below the biceps muscle belly). The lower part of the cuff, which was tightened to the forearm, served to make the upper part of the cuff rotate as the upper arm rotated. Because pro- and supination of the forearm were not prohibited and because there were two hinges at the side of the elbow joint, the arm was free to move. The cuff was constructed of thin PVC and was light of weight; it was covered on the inside with chamois leather for comfort. On the subject's back, near the lower cervical vertebrae, a PVC rigid body with three IREDs was placed to record the position of the trunk. The analyses were restricted to the kinematics of the finger-tip trajectories and the kinematics of two joints, viz., the elbow and the shoulder.

2.3. Data analysis

The tangential velocity was calculated by differentiation of the finger-tip displacement data, followed by low-pass filtering (3rd order, zero phase lag, cut-off frequency 12 Hz). By means of a semi-interactive computer program the data were segmented into three submovements (to T1 on the screen, from T1 to T2, and back to the start) on the basis of local velocity minima. For each submovement, the mean tangential velocity of the finger tip was calculated. To determine movement accuracy in workspace, the distance between the 3D position of the marker on the finger-tip at the time of impact and the centre of the target on the frontoparallel screen was calculated.

To study movement trajectories in joint space, angular joint excursions were extracted off-line from the calculated positions of wrist, elbow, and shoulder joints and the orientation of the back. The elbow angle was defined as the enclosed angle between the upper arm and the forearm, with full extension as 180°. Elevation was defined as the angle of the sagittal projection of the upper arm and a vector pointing forward through the trunk. [1] Azimuth was defined as the angle of the projection of the upper arm in a horizontal plane relative to the forward direction. Joint space was defined as the three-dimensional space consisting of the elbow angle and the elevation and azimuth angles of the shoulder.

Work-space trajectories and joint-space trajectories were low-pass filtered (3rd order, zero phase lag, cut-off frequency 12 Hz). In both workspace and joint space, planes were fitted to the trajectories of each of the three submovements separately. The fitting procedure is described in Appendix A. The three-dimensional curvature of the finger-tip and joint-space paths was calculated by means of a method described by Koenderink (1990) (see Appendix B). The mean 3D curvature of each submovement, in both workspace and joint space, was determined as the average curvature of that part of the submovement in which the tangential velocity of the finger tip exceeded 30% of the peak velocity that was reached in the entire experiment by the respective subject. The three submovements were treated separately in further analyses for reasons mentioned in the introduction section. The mean of the dependent variables across the six replications per experimental condition served as cell entries for within-subject repeated measures ANOVAs. The design specifications are formulated in the relevant results sections.

3. Results

3.1. Performance measures

One subject was excluded from the analysis because he behaved differently from the other subjects. Rather than producing reaching movements with both his arm and hand, he showed a strategy of an arm movement bringing the hand towards the screen first and then quickly rotating his wrist so that the index finger hit the screen. This resulted in high peak velocities of the finger-tip at the end of the first two submovements. The movements of this subject differed qualitatively from those produced by the other subjects.

Table 1 shows the mean tangential velocity of the finger tip as a function of Target Size. The velocity data of the three submovements were evaluated separately by means of three ANOVAs according to a 3 Starting Positions (in front of longitudinal

[1] Note that usually elevation is defined as the angle between the upper arm and the trunk. The present definition of elevation was considered sufficient for our research purpose.

Table 1
Mean velocity (m/s) and standard deviation for three submovements as a function of target size

Target size(mm)	Submovement		
	1	2	3
6	1.24 ± 0.22	1.04 ± 0.20	1.16 ± 0.22
12	1.30 ± 0.32	1.11 ± 0.31	1.21 ± 0.33
25	1.34 ± 0.35	1.18 ± 0.35	1.23 ± 0.36
50	1.39 ± 0.37	1.25 ± 0.39	1.26 ± 0.37
100	1.46 ± 0.43	1.38 ± 0.49	1.29 ± 0.40

body axis, 20 cm to the right, 40 cm to the right) × 2 Target Positions (first target left versus first target right) × 5 Target Sizes (see method section) repeated measures design. Mean velocity significantly increased as function of Target Size for each submovement ($F(4,10) = 8.30$, $p < 0.01$, $F(4,10) = 9.93$, $p < 0.01$, and $F(4,10) = 3.89$, $p < 0.01$, respectively). It can be concluded that Target Size was effective in eliciting speed variations. End-point accuracy analyses revealed a systematic co-variation of accuracy and speed where accuracy was higher at lower movement speed.

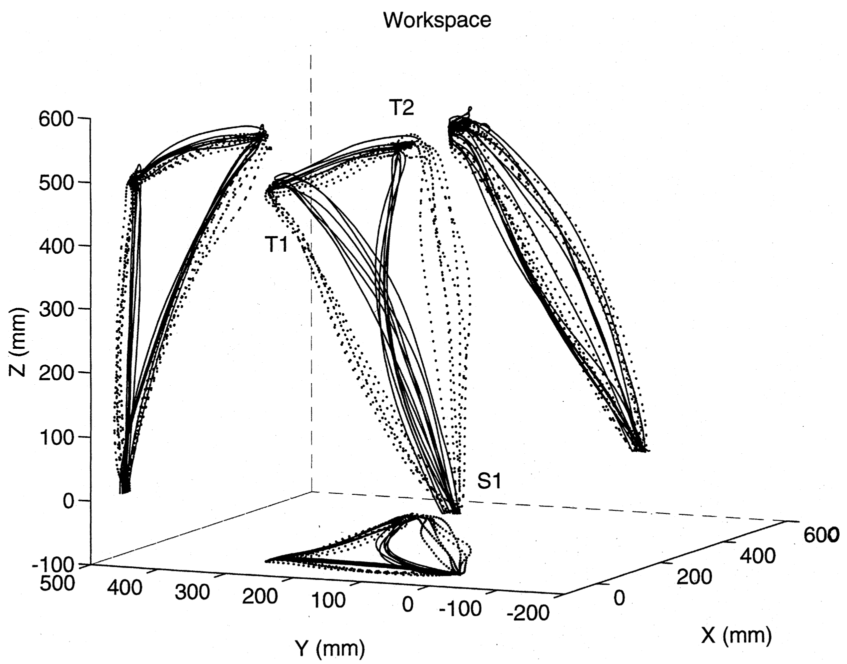

Fig. 2. 3D plot of the finger-tip trajectory in workspace. In the middle of the figure 3D trajectories are shown. The solid lines represent six replications of a counter-clockwise movement from the left starting position to the right target, then to the left target and back to the left starting position (S1 → T2 → T1 → S1). The dashed lines represent six replications of a clockwise movement (S1 → T1 → T2 → S1). On the left, the projection on the XZ-plane (= the frontoparallel screen) is shown, on the right a projection on the YZ-plane and below a projection on the horizontal XY-plane.

Fig. 2 shows the 3D finger-tip paths in workspace (central paths), and the corresponding 2D projections on the XY plane (bottom), YZ plane (top right) and XZ plane (left), of twelve replications of a three-segment movement pattern performed by a subject in a 6 mm target-size condition. The solid lines represent movements from the left starting position (S1), to the right target (T2), to the left target (T1), and back to start. The dashed lines represent the six replications of the similar movement pattern in the reverse direction (i.e., S1 → T1 → T2 → S1). The 3D paths show that the trajectories from S1 towards the screen, both to T1 and T2, differ with respect to curvature from the trajectories in opposite direction from the screen to S1. Furthermore, the tendency to realize a perpendicular impact on the frontoparallel screen is demonstrated at the top left of the *YZ*-plane projection of the trajectories. Finally, the *XZ*-plane projections of the trajectories show that forward movements in the midsagittal plane were more straight than the diagonal inward movements from T2 on the screen to S1 on the platform which was located in front of the subject's longitudinal body axis.

Fig. 3 shows the 3D joint-space paths corresponding with the 3D finger-tip paths shown in Fig. 2. It shows that shoulder elevation and elbow excursion were mainly responsible for movements to and from the frontoparallel screen and elbow excursion and azimuth of the shoulder were mainly involved in the movement between the two targets on the frontoparallel screen. Clearly, the curvature of the latter move-

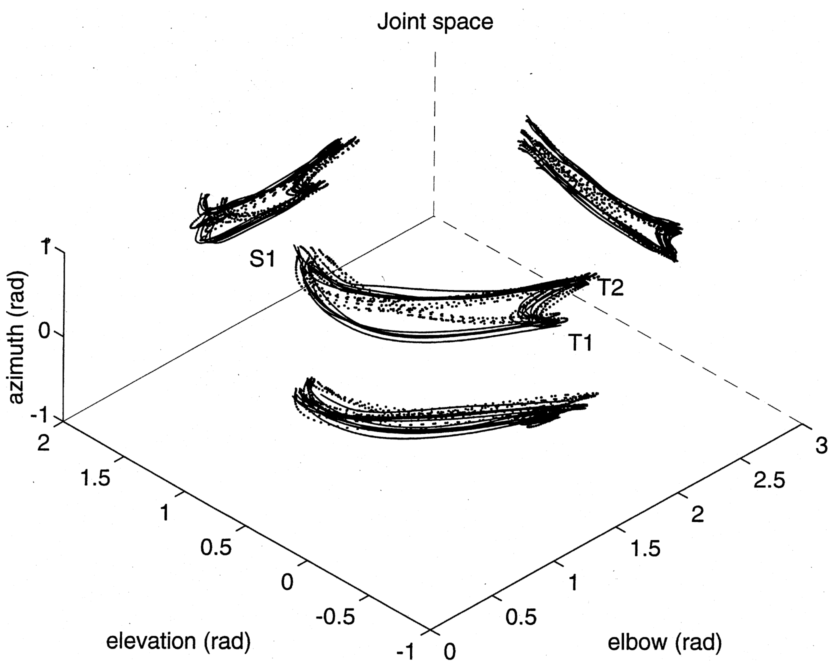

Fig. 3. 3D plot of the same movements as shown in Fig. 2, but for the trajectories in joint space. From this point of view the clockwise trajectory in workspace is a counter-clockwise trajectory in this figure and vice versa.

ment was larger than the curvature of the former two movements. This can be explained by the fact that the subject had to lift his finger from the frontoparallel screen by flexing his elbow after which an elbow extension resulted in impact on T2. The elbow flexion and extension was responsible for the high curvature of the joint-space path of the second submovement.

3.2. Degree to which submovements were produced in 2D planes

In Fig. 4 the mean errors of the plane-fitting procedures are given per submovement. The error was defined as the mean distance of the data points to the

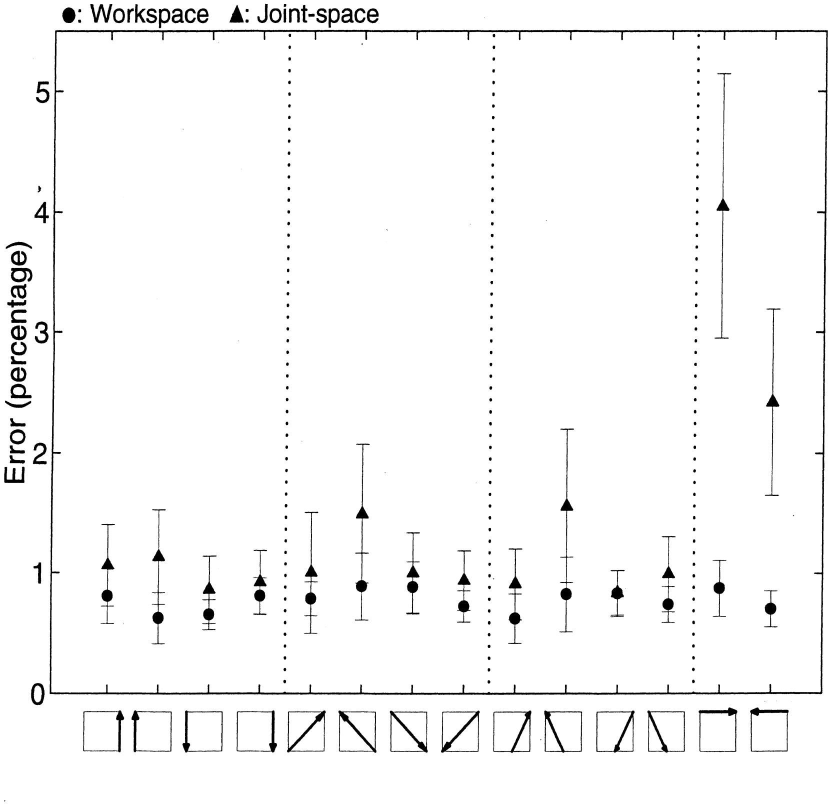

Fig. 4. Mean errors and standard deviations as a function of movement type. The error was defined as the mean perpendicular distance of all data points of a submovement to the best-fitting plane. The errors in workspace (filled circles) as well as joint space (filled triangles) are given as percentages of the observed straight-line distance of the respective submovements. On the horizontal axis icons depict the movement type. A square should be seen as the 60° tilted plane, with two target positions in the upper left and upper right corner and three starting positions at the bottom. Dashed vertical lines separate the movements with respect to the amount of lateral hand displacement involved.

plane divided by the straight-line distance between the adopted starting and realized target position. Consequently, the error data of the fitting of 2D planes to the 3D workspace and joint-space trajectories are expressed as proportions and they are therefore comparable. In workspace, the mean perpendicular distance of data points to the best-fitting plane was about 1% of the straight-line distance of the submovement. Whereas, in workspace, the movements to and from the frontoparallel screen in the midsagittal plane (Fig. 4, from left to right, the second and third filled circle) had the least error, the diagonal movements from the right and middle starting position towards the left target (Fig. 4, from left to right, the sixth and tenth filled circle) and back had the largest errors. In joint space fitting errors were a little larger than in workspace, but more for movements towards the screen than for backward movements. Fitting errors of joint-space trajectories between both targets on the screen were larger, about 4%. The joint-space trajectories of these constrained movements were more curved in three dimensions than other submovements, because there were two joint reversals, both for elbow angle and shoulder elevation, while at the same time the azimuth angle changed.

Fig. 5 shows the mean orientation of the planes, pooled across subjects, that were fitted to individual trajectories in workspace. For the submovement from S1 to T1 a complete plane is shown, filled with grey. Of the other planes only the intersections with the horizontal platform and with the frontoparallel screen are shown, solid lines for movements towards the screen and dotted lines for movements to the starting position. Movements straight to and from the screen were produced in an approximately sagitally-oriented plane. The diagonal movements were produced in planes that were oriented obliquely. The top of the plane hangs over to the side to which the movement is going, while the base is about perpendicular to the frontoparallel

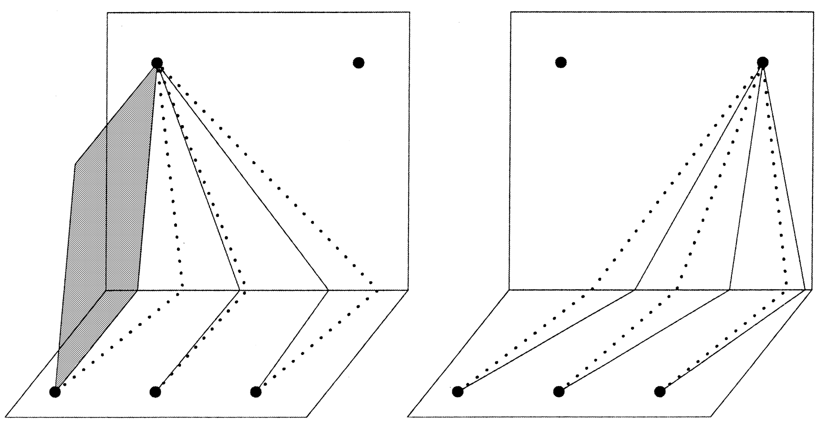

Fig. 5. An overview of the orientations of the planes fitted to the trajectories. The left panel shows submovements to and from T1, the right to and from T2. For the submovement from S1 to T1 a complete plane is shown, whereas for the other submovements only the intersections with the horizontal platform and with the frontoparallel screen are shown, solid lines for movements towards the screen and dotted lines for movements back to the starting position.

screen. The corresponding planes in joint space are not shown, but they indicate that most of the trajectories in joint space took place in the elbow-elevation plane.

3.3. Curvature variations

Fig. 6 shows the mean 3D curvature of the central parts of the workspace paths (filled circles in upper panel) and joint-space paths (filled triangles in lower panel) per submovement. It can be seen that there are only small fluctuations. Nevertheless, these fluctuations have a systematic pattern, similar to the plane-fitting errors (see Fig. 4). Movements in the midsagittal plane were less curved, while diagonal movements from the right starting position towards the left target position were more curved. In joint space the opposite was observed. Furthermore, there was a negative correlation between joint-space curvature and workspace curvature for the unconstrained 3D movements ($R = -0.75$, df = 11, $p < 0.01$). The curvature data of the workspace and joint-space paths were evaluated separately by means of two ANOVAs per submovement according to a 3 Starting Positions (in front of the longitudinal body axis, 20 cm to the right, 40 cm to the right) $\times$ 2 Target Positions (first target left versus first target right) $\times$ 5 Target Sizes (see method section) repeated measures design.

With respect to path curvature in workspace, the finger-tip trajectories of the first submovement towards T1 were more curved than the finger-tip trajectories to T2 ($F(1,10) = 6.48$, $p < 0.05$), while for the second submovement finger-tip trajectories to T2 were more curved ($F(1,10) = 8.44$, $p < 0.05$). Starting Position, which is actually

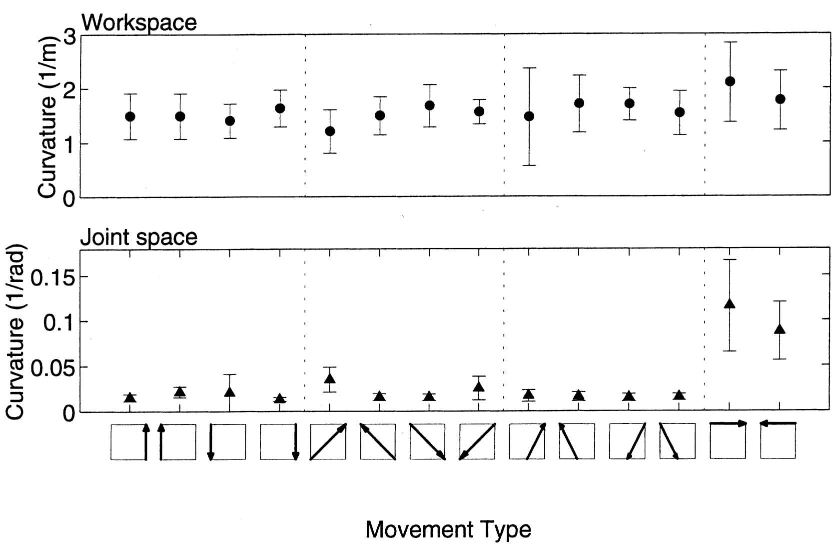

Fig. 6. Mean global curvature of the finger-tip paths (1/m, upper panel) and joint-space paths (1/rad, bottom panel) as a function of movement type. On the horizontal axis icons depict the movement type.

the final destination of the entire movement sequence, significantly influenced the curvature of finger-tip path of the third submovement ($F(2,10) = 9.77$, $p < 0.01$). There was an interaction between Starting Position and Target Position: whereas for S3 there was almost no difference in curvature when pointing to T1 or T2, for S1 and S2 curvature was higher for pointing to T1 than for pointing to T2 ($F(1,10) = 6.73$, $p < 0.01$). No further interactions were found on workspace path curvature.

With respect to path curvature in joint space, the joint-space trajectories of the first submovement towards T2 were more curved than joint-space trajectories towards T1 ($F(1,10) = 10.17$, $p < 0.01$), and also for the second submovement joint-space trajectories to T2 were more curved than joint-space trajectories to T1 ($F(1,10) = 8.18$, $p < 0.05$). Joint-space trajectories of the first submovement from S1 were more curved than from S2 and S3 ($F(2,10) = 35.08$, $p < 0.01$). Also joint-space trajectories of the third submovement towards S1 were more curved than those to S2 and S3 ($F(2,10) = 12.20$, $p < 0.01$). There was an interaction between Starting Position and Target Position. For S2 and S3 there was almost no difference in curvature for pointing to T1 or T2, but for T1, joint-space trajectories of movements to T2 were about twice as curved as the movements to T1 ($F(1,10) = 14.74$, $p < 0.01$). No further interactions were found on joint-space path curvature.

Fig. 7 shows the mean curvature of the finger-tip path of the three submovements as a function of Target Size (top panel). The curvature of each submovement increased as Target Size, and thus movement speed, increased. The second submovement, which was from T1 to T2 on the screen, was, for all target sizes, more curved than the first and the third submovements and increased more as movement velocity increased. The influence of Target Size was significant for the second and the third submovements ($F(4,10) = 28.65$, $p < 0.01$, and $F(4,10) = 8.63$, $p < 0.01$, respectively), but not for the first submovement ($F(4,10) = 1.21$, ns). The bottom panel of Fig. 7 shows the mean curvature of the three submovements in joint space. Only joint-space paths of the second submovement were more curved as Target Size increased ($F(4,10) = 3.59$, $p < 0.05$), for the first and third submovements the effects were absent ($F(4,10) = 1.02$, ns and $F(4,10) = 1.37$, ns, respectively). The mean curvature of the joint-space path of the second submovement was about five times higher than that of the first and the third submovements.

4. Discussion

The results of the present study show that the 3D reaching movements between a horizontal platform and a frontoparallel screen can very well be described as movements that were produced in a single plane. The mean distance between the paths and the best-fitting planes was only 1% of the straight-line distance between the starting and target positions, both in workspace and in joint space. Only for the constrained movements between the two targets, the error in joint space increased to 4%. For the movements from S1 and S3 (see Fig. 1) straight towards the frontoparallel screen the small error was expected, because for these movements the starting and target positions were located in sagittal planes. By raising the arm

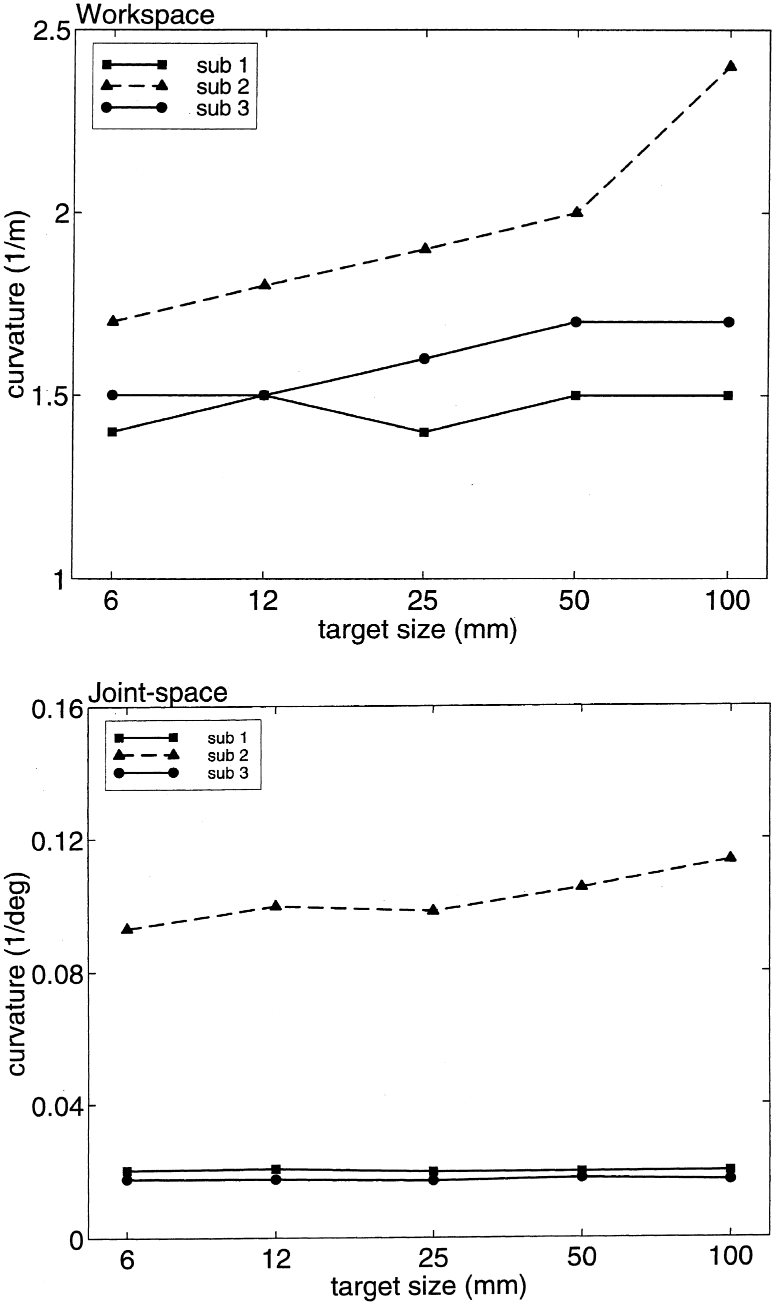

Fig. 7. Mean global curvature of the extrinsic finger-tip path (1/m, top panel) and joint-space path (1/deg, lower panel) as a function of target size (mm) per submovement. On the horizontal axis icons depict the movement type.

(against gravity) and by approaching the screen perpendicularly, the movement can be performed within one plane. Indeed, finger-tip trajectories in the midsagittal plane were less curved and also the plane-fitting error was the smallest for these movements. For oblique movement directions, the situation was more complex. Both the extent to which these trajectories were produced within a plane and the 3D curvature of these trajectories was influenced by two factors. First, the subject had to lift his/her finger, hand, and arm by moving upwards, then he/she had to move towards the screen while realizing a lateral displacement. Finally, the frontoparallel screen had to be approached perpendicularly. So, the first part of the finger-tip path in workspace of these oblique movements consisted of a movement in the vertical direction and the final part consisted of a horizontal screen-approaching movement. A larger lateral displacement was required as the movement directions were more oblique. Inspection of individual workspace trajectories showed that the vertical deviation of the straight line in the first part of the submovement appeared to be of less importance for the orientation of the fitted planes than the final perpendicular approach to the target screen. This caused the fitted planes to be oriented more obliquely (with their base perpendicular to the target screen) as the movement directions were more oblique. Given the complexity of the oblique movements it was surprising that these movements could also be fitted by planes. In workspace the oblique movement from the left starting position to the right target was least curved of all submovements and the plane-fitting error was also small. In joint space though, the curvature was highest for these movements, but nevertheless the plane-fitting error was small, which means that in joint space the trajectory also fits well within a plane, as long as the movement is not constrained.

Recently it has been shown that pointing and grasping movements in joints with three degrees of freedom, such as the shoulder, are subject to a reduction of degrees of freedom (Gielen et al., 1997). This reduction implies that, for shoulder movements, the rotation vectors describing the orientation of upper arm in 3D space are located in a single plane, i.e., the control of a rotation of a 3D joint is reduced from a 3D to a 2D problem. Although this finding does not necessarily imply that movements occur in a single plane, we consider the present findings as additional evidence indicating that people are inclined to produce movements in 2D rather than in 3D.

Despite the fact that people strive for movement simplification by moving in a 2D plane, trajectories were curved in the present study. As was shown earlier for 2D movements (Haggard and Richardson, 1996; Atkeson and Hollerbach, 1985), the present study shows systematic curvature variations as a function of movement direction. The left-to-right movements were more curved than the other submovements, but this was probably caused by the fact that these were constrained movements. In order to avoid collision with the screen, a curved trajectory in workspace had to be followed, for which also a curved trajectory in joint space was necessary. For movements towards the screen, finger-tip paths of movements straight ahead were not straighter than those of movements that were more left-right oriented, as found by Haggard and Richardson (1996) in the horizontal plane. On the contrary, the straightest submovement in workspace was the most oblique movement direction from the left starting position to the right target. As expected, the submovement that was the least curved in workspace was the one that was most curved in joint space. This is a movement direction in which a joint-reversal is necessary in order to move to the target and at the same time to be able to approach the target screen perpendicularly, which is what people generally strive for (Brenner and Smeets, 1995). The inverse relationship between curvature in workspace and in joint space was expected, because in order to move along a straight line in workspace, the path in joint space has to be curved, at least for some movement directions (Morasso, 1981).

Workspace paths of movements from the screen back to the starting position were in general more curved than of movements towards the screen. Probably because there were no speed and accuracy demands on the final submovement in the present task, the subjects simply dropped the arm, by bending the elbow, lowering the arm, and rotating the upper arm about its longitudinal axis more or less synchronously. During task performance it was frequently noticed that subjects slipped with their finger off the horizontal platform and sometimes even missed it completely.

As stated in the introduction, if joints rotate in synchrony, the corresponding joint-space trajectory will be less curved, resulting in a more curved workspace trajectory. Together these results support the suggestions made by Cruse and Brüwer (1987) that reaching movements reflect a compromise between the tendency of subjects to try to produce simultaneously a straight line in workspace and a straight line in joint space. The larger the spatial accuracy demands on point-to-point aiming movements, the less curvature in workspace of the end-effector paths will be observed. If spatial accuracy demands are low, however, strongly curved end-effector paths in workspace are likely to be observed that correspond to straight-line trajectories in joint space.

Mean tangential velocity increased more rapidly as a function of target size for the second submovement than for the first and the third submovements. This finding points at an additional cause of speed variations, most likely the impact of the screen. It was observed in the present task that the subjects' index finger frequently bounced off the screen as the target was pointed at with a high speed.

Irrespective of local high curvature due to counteracting gravity at the start of the movement from zero velocity and the geometrical constraints of approaching a target perpendicularly to a surface (Brenner and Smeets, 1995), the central parts of the finger-tip paths of the reaching movements were found to be more curved as movement speed increased. The increase of global curvature of finger-tip paths with increasing speed was expected and points out that faster movements are not likely to be planned in workspace only. Global curvature of joint-space paths did not change however as a function of speed, except for the second submovement. Path curvature of the second, constrained, movement increased as speed increased, both in workspace and in joint space, most likely due to external factors, resulting from the impact of the finger with the frontoparallel screen. The fact that joint-space paths of various speeds were of relatively constant curvature, though, does not provide a clear argument that those movements are purely planned in joint space. The present results therefore indicate, in our view, that in reaching movements optimization processes in both workspace and joint space jointly determine the trajectory formation process: a trade-off between path curvature in workspace and joint space was clearly present.

In sum, the curvature of the finger-tip paths in workspace in the presently investigated three-segment movement pattern in a 60° tilted horizontal plane increased as velocity increased whereas joint-space path curvature did not vary as a function of velocity. Position and direction of the movement also influenced the global 3D curvature. The most striking result of the present study, however, was that subjects tend to produce 3D reaching movements by means of curved trajectories that are restricted to two dimensions, i.e. to a plane, both in workspace and in joint space.

Appendix A. The plane-fitting procedure

The plane-fitting procedure consisted of a minimization of the mean squared distance of the data points to a plane. A plane is defined by: $ax + by + cz + d = 0$. The minimization was done by a singular value decomposition program (Mathworks). The error measure was defined as the mean absolute distance of the data points to the best-fitting plane and was used as an index of the extent to which the trajectory was fitted by a plane. To allow for comparisons of the results in workspace and in joint space, the error measure was normalized by dividing the mean absolute distance of the observed trajectory to the best-fitting plane by the observed straight-line distance between the starting position and target position.

Appendix B. Local 3D curvature

For calculating the local curvature of a 3D trajectory (either in workspace or joint space) a method of Koenderink (1990) was used. Virtual equidistant positions on the original path were calculated at small distances (i.e., 0.2 mm and 0.02° in workspace and joint space, respectively) from each data point by means of interpolation. For each sample, and the two interpolation points preceding and following the sample, the orientation of a plane was determined in which the curvature was the highest. On the basis of this plane, a new frame of reference was defined of which the X'-axis was the tangent of the trajectory at that sample and the Y'-axis was perpendicular to the tangent in the plane, pointing to the centre of a circle fitted through the three points. The Z'-axis was defined perpendicular to the X'- and Y'-axes, according to a right-handed orthogonal co-ordinate system. In the present analysis, only the curvature in the $X'Y'$-plane was calculated. To this end, a trajectory part of four samples was expressed in the new frame of reference and a polynomial ($Y' = a + bX' + cX'^2$) was fitted to these samples. The value of c was used as the measure of curvature. The torsion (curvature out of the plane) was neglected, because it is generally about 1000 times smaller than the curvature in the $X'Y'$-plane. The applied algorithm to determine the path curvature did not imply that the curvature measurement was reduced to a 2D curvature measurement, since the orientation of the plane in which the curvature was highest, could change from sample to sample.

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