RAPID COMMUNICATION

Constrained and Unconstrained Movements Involve Different Control Strategies

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Desmurget, Michel, Michael Jordan, Claude Prablanc, and Marc Jeannerod. Constrained and unconstrained movements involve different control strategies. J. Neurophysiol. 77: 1644–1650, 1997. This experiment was carried out to test whether or not the rules governing the execution of compliant and unconstrained movements are different (a compliant motion is defined as a motion constrained by external contact). To answer this question we examined the characteristics of visually directed movements performed with either the index fingertip (unconstrained) or a hand-held cursor (compliant). For each of these categories of movements, two experimental conditions were investigated: no instruction about hand path, and instruction to move the fingertip along a straight-line path. The results of the experiment were as follows. 1) The spatiotemporal characteristics of the compliant and unconstrained movements were fundamentally different when the subjects were not required to follow a specific hand path. 2) The instruction to perform straight movements modified the characteristics of the unconstrained movements, but not those of the compliant movements. 3) The target eccentricity influenced selectively the curvature of the “unconstrained—no path instruction” movements. Taken together, these results suggest that compliant and unconstrained movements involve different control strategies. Our data support the hypothesis that unconstrained motions are, unlike compliant motions, not programmed to follow a straight-line path in the task space. These observations provide a theoretical reference frame within which some apparently contradictory results reported in the movement generation literature may be explained.

INTRODUCTION

A major problem in the theoretical field of motor control concerns the nature of the variables used by the CNS to plan the movement (Bizzi et al. 1984; Morasso 1981; Soechting and Lacquaniti 1981). One of the major theories proposed during the last decades with regard to this question suggests that reaching movements are encoded by planning hand trajectories in extracorporal space. In agreement with this view, numerous experiments have demonstrated that point-to-point movements followed roughly straight-line paths, irrespective of the initial and final locations of the hand within the workspace (Flash and Hogan 1985; Morasso 1981). The generality of this result was, however, called into question by several studies showing that the hand path curvature observed during visually directed movements was both significant and related to the movement direction (Atkeson and Hollerbach 1985; Haggard and Richardson 1996; Lacquaniti et al. 1986).

To understand the apparently contradictory results previously reported, it is worth noting that an important methodological difference generally exists between the experiments describing straight and curved motions: the presence or absence of an “intermediate tool” used to record the movement (hand-held cursor, pen, manipulanda…). Whereas the experiments showing consistently curved paths (Atkeson and Hollerbach 1985; Haggard and Richardson 1996; Lacquaniti et al. 1986) utilized unconstrained movements, the studies emphasizing the linearity of arm trajectory (Flash and Hogan 1985; Morasso 1981) utilized compliant motions (a compliant motion is defined as a motion constrained by external contact). This observation might suggest that compliant and unconstrained movements involve different planning strategies. The main purpose of the present study was to test this hypothesis.

METHODS

Apparatus

Eight right-handed subjects participated in this experiment. All presented normal visual acuity and were totally naive about the purpose of the study. The experimental device (Fig. 1) consisted of a horizontal table in front of which the subjects were seated comfortably. A screen, coupled with a video graphics array (VGA) projector, was suspended over the pointing surface. Moreover, a half-reflecting mirror was placed between the subjects’ eyes and the table. The subjects saw the virtual images of small dots (pointing targets) through the mirror, in the plane of the pointing table. Four targets were used in the present experiment. The targets were located on a circle (radius 30 cm) at 0, 20, 40, 60, and 80° in the right hemispace. The hand starting position was located at the center of the target circle. The subject’s head was aligned with the “starting point 0° target” axis, 35 cm above the starting position. The 0° target was used as a gaze fixation point.

Experimental conditions and procedure

The basic experimental design resulted from the combination of three factors. The first factor, called “external constraint factor,” was related to the mechanical constraints imposed on the movement. Two conditions were then studied: unconstrained pointing (U) and pointing with the use of a hand-held cursor (compliant condition, C; Fig. 1C). Note that the subject’s fingertip rested on the table surface at the start and termination of the unconstrained movements. The second factor, called “path instruction factor,” was related to the internal constraints imposed on the movement. Two conditions were examined: free path (F), and straight-line path (S). In the first case (F), no instruction was given regarding hand path, and the subjects were instructed to “move the fingertip from the starting position to the target as quickly and accurately as possi-
FIG. 1. Schematic representation of the experimental apparatus (A and B) and of the cursor used to produce the compliant motions (C: subjects were required to hold the cursor with the index fingertip in the middle of the circle labeled c). VGA, video graphics array.
ble.’’ In the second case (S), a constraining instruction was given regarding the shape of the hand path, and the subjects were instructed to ‘‘move the fingertip from the starting position to the target as quickly and accurately as possible, following a straight-line path.’’

The third factor, called ‘‘target eccentricity factor,’’ was related to the eccentricity of the target. Four target eccentricities were considered: 20, 40, 60, and 80°.

Considering the results of a preliminary experiment showing that movement duration (MD) was consistently less in UF than in the other conditions, two control conditions were added to the basic experimental design: UFT and UST. These conditions were identical to UF and US, respectively, except that the subjects were instructed to get the movement in a given temporal window (these controls were performed to check whether the differences observed between UF and the other conditions could be related to velocity variations). For UFT, the reference duration was equal to the average duration recorded during US. For UST, the reference duration was equal to the average duration recorded during UF. For UFT and UST, a successful trial was one whose MD was within 1 SD of the mean of the reference condition. During the session, subjects were informed about the MD after each trial, and were instructed to move faster or slower when necessary. Only the movements satisfying the time criterion were recorded. Incorrect movements were presented again later in the session, unknown to the subject.

Hand position was delivered to the subjects during the intertrial period only (finger position disappeared at movement onset). This was done to prevent both planning bias (Ghilardi et al. 1995) and dynamic corrections based on the simultaneous vision of the target and of the moving limb (Prablanc and Martin 1992). During the intertrial period the subjects could see, through the mirror, a white filled square representing the virtual image of the fingertip on the table. At the beginning of each trial, the subjects were instructed to look at the fixation point (red 0° target). After a randomly selected fixation time (0.5 s < fixation time < 2 s), a tone was given and a target was presented. The subject had to look and point at this target. Each of the four targets was presented 10 times in a random order. After movement completion, subjects were instructed to return to the starting position (a small circle was presented through the mirror and the subject was asked to place the virtual image of the fingertip within this circle).

Recording technique and data analysis

Movement of an infrared emitting diode located on the index fingertip was recorded at a frequency of 200 Hz with an OPTOTRAK system. The kinematic landmarks analyzed in this experiment were movement latency (ML) and MD. The onset and the end of the hand movements were computed automatically with the use of the following thresholds: hand velocity = 8 cm/s, hand acceleration = 150 cm/s² (these values were chosen to statistically fit with the values obtained from a visual windowing).

Inasmuch as the compliant movements are by definition constrained in the horizontal plane, hand paths were computed and compared in this plane for all the conditions (the small curvature observed with respect to the vertical plane for the unconstrained movements was neglected in the present analysis). Linearity of movement trajectories was estimated with the use of the ‘‘linearity index’’ (LI) initially proposed by Atkeson and Hollerbach (1985). For each movement, the equation of the straight line joining the start and endpoints of the movement was computed. The largest deviation (d) of the arm trajectory from that line was then determined. The LI was defined as the ratio of d to the length of the segment connecting the start and endpoints of the movement.

Movement endpoint scatter (variable error), which has proved to be a relevant parameter to infer the planning variables underlying the kinematic features of reaching movements (Flanders et al. 1992; Gordon et al. 1994), was also analyzed in the present study. To determine the characteristics of the variable errors the 95% endpoint confidence ellipses were computed for each subject, each experimental condition, and each eccentricity of the target (Johnson and Wichern 1982). Two variables were then extracted: 1) ‘‘the shape of the confidence ellipses,’’ characterized by the ratio (R) of the lengths of the axis of the confidence ellipses (major axis/minor axis); and 2) ‘‘the direction of the confidence ellipse,’’ characterized by the angle between the major axis of the ellipse and the average direction of the movement (this latter parameter was defined as the line connecting the starting point and the mean endpoint).

Statistical analysis

To test for the existence of significant differences between the compliant and unconstrained movements, a three-way analysis of variance (ANOVA) with repeated measures was performed (main analysis). The repeated measures factors were: external constraint (2 levels: U and C), path instruction (2 levels: F and S), and target eccentricity (4 levels: 20, 40, 60, and 80°).

To test whether the spatial characteristics (curvature, endpoint distribution) of the UF movements could be related to velocity factors (i.e., to biomechanical distortions), an additional three-way ANOVA with repeated measures was performed on the U conditions (control analysis). The repeated measures factors were: path instructions (2 levels: F and S), ‘‘temporal requirements’’ (2 levels: F and C), and target eccentricity (4 levels).

The Tukey significant difference test was used for post hoc comparisons of the means. Threshold for statistical significance was set at 0.05.

RESULTS

Only the statistical analyses relevant to our purpose are reported in the following. In particular, the interactions between experimental factors are reported only when significant. Moreover, the effect of the target eccentricity factor is not mentioned except when this factor interacts with the other experimental factors.

Main analysis

MOVEMENT LATENCY. As demonstrated by the significant interaction observed between the path instruction and the external constraint factors [F (1,7) = 22.35, P < 0.0025], the instruction to move the fingertip along a straight-line path did not exert the same influence on ML for the compliant and unconstrained movements. Whereas the time necessary to initiate compliant motions was similar irrespective of the path instruction (CF: 444 ms; CS: 441 ms), the time needed to initiate unconstrained movements was significantly and considerably increased when the subject were asked to follow a straight-line path (UF: 329 ms; US: 451 ms). The ML observed for the US condition was not significantly different from that recorded for the CF and CS conditions.

MOVEMENT DURATION. A significant interaction was observed between the external constraints acting on the movement and the path instruction [F (1,7) = 15.41, P < 0.01]. Whereas the MD was similar for the compliant motions, irrespective of the path instruction (CF: 559 ms; CS: 542 ms), it was significantly increased for the unconstrained motions when the subjects were asked to follow a straight-
FIG. 2. Variations of the hand path curvature according to the target eccentricity for all the experimental conditions (mean and interindividual SD). As shown on the figure, movement curvature, which remains roughly stable according to target location for the unconstrained—straight path (US), the compliant—straight path (CS), and the compliant—free path (CF) conditions (none of the observed differences reached statistical significance), increases significantly with target eccentricity for the unconstrained—free path (UF) condition. Note that the temporal factor does not consistently influence the movement path curvature as shown by the absence of significant differences between US-UST and UF-UFT. Note also that the hand path curvature is consistently larger for these two latter conditions than for the other conditions, which are not significantly different according to each other.

The hand path curvature was not significantly different for the US, CF, and CS conditions.

PATH CURVATURE. Regarding the hand path curvature, a significant interaction was observed between the external constraints acting on the movement, the path instruction, and the target eccentricity \( F(3,21) = 14.88, P < 0.0001 \). The physical meaning of this statistical interaction could be summarized as follows (see Figs. 2 and 3).

The UF condition was the only condition for which the index of curvature of the movement (LI) was influenced by the target eccentricity: whereas LI increased significantly with target eccentricity for the UF condition, it was independent from this factor for the US, CF, and CS conditions.

The hand path curvature was significantly higher in the UF than in the other experimental conditions (UF was different from US, CF, and CS, for all the eccentricities of the target).

The hand path curvature was not significantly different for the US, CF, and CS conditions considered two by two.

ENDPOINT DISTRIBUTIONS. As shown in Fig. 3 for a representative subject, the endpoint distributions varied consistently according to the experimental factors. As regards endpoint distribution elongation, the ANOVA demonstrated the existence of a significant interaction between the external constraint and path instruction factors \( F(1,6) = 12.94; P < 0.01 \). Post hoc analysis performed with respect to this interaction showed that endpoint cluster elongation was significantly less in UF (1.35) than in the other conditions (CF: 2.27, CS: 2.19, US: 2.46; these 3 conditions were not different from each other). These significant differences in the endpoint cluster elongations were associated with consistent differences in the endpoint cluster orientations. Whereas it was not possible to detect a preferential orientation for the UF clusters, due in particular to the absence of a clear elongation for most of the clusters related to this condition, highly consistent patterns were observed for the CF, CS, and US conditions. In these conditions, the major axes of the endpoint distributions were generally close to the average movement direction for all the subjects, and all the target eccentricities (we only observed 16 clusters—of 96—for which the direction of the principal axis was closer to a direction perpendicular to the mean direction of the movement than to the mean direction of the movement).

Control analysis

MOVEMENT LATENCY. Although ML tended to be slightly longer in the temporally constrained than in the temporally free conditions (UF: 329 ms; UFT: 355 ms; US: 451 ms; UST: 459 ms), the ANOVA indicated that these differences were not significant. Neither the main effect of the temporal factor \( F(1,7) = 1.63, P > 0.25 \) nor the interactions involving it were significant. This identity between the ML of the US-UST movements and UF-UFT movements is compatible with the hypothesis that the planning processes were the same in US-UST and in UF-UFT.
MOVEMENT DURATION. As expected, a significant interaction was observed between the path and temporal requirements for MD \( [F(1.7) = 16.54, P < 0.005] \). As shown by post hoc analysis, MD was identical for the UF-UST (453 and 458 ms) and US-UFT (566 and 563 ms) pairs.

PATH CURVATURE. Variations of path curvature are represented in Figs. 2 and 3 according to the temporal requirements, path instructions, and target eccentricity factors. As shown in these figures, the temporal factor did not consistently influence the movement path curvature (for a given eccentricity of the target, the path curvature was the same for the UF-UFT and the US-UFT pairs). This graphic observation was confirmed by the ANOVA, which showed that neither the main effect \( [F(1,7) = 5.35, P > 0.05] \) nor the interactions involving the temporal factor were significant. This result indicated that the consistent curvature observed in the UF condition was not related to the fact that movement velocity was significantly higher in this condition.

ENDPOINT DISTRIBUTIONS. For all the subjects, the endpoint distribution patterns tended to be similar for the temporally free and temporally constrained conditions. As regards the endpoint distributions elongations, ANOVA showed that the ratio of the major to the minor axes of the confidence ellipses were not statistically different for the UF-UFT (1.35 and 1.34) and US-UFT (2.46 and 2.57) pairs. For these two latter conditions, the same typical orientation was observed: like the US clusters, the UST clusters were generally oriented along the axis of the mean direction of the movement (for UST, we observed 7 clusters —of 32—for which the direction of the principal axis was closer to a direction perpendicular to the mean direction of the movement than to the mean direction of the movement). These results, which are illustrated in Fig. 3 for a representative subject, indicated that the absence of typical endpoint scatter orientation for the UF movements was not related to the higher velocity observed in this condition.

DISCUSSION

Taken together, the results of the present study suggest that compliant and unconstrained movements involve different planning strategies. This conclusion is supported by three main observations, which will be briefly examined in the following.

Compliant and unconstrained movements present fundamentally different characteristics

Three main differences were observed between the compliant and unconstrained movements when the subjects were not required to follow a specific hand path. 1) The ML and MD were significantly greater in the C than in the U condition. 2) The degree of path curvature was significantly higher in the U than in the C situations. 3) The movement endpoint distribution was both more elongated and closer to the average movement direction in the C than in the U conditions. Note, as demonstrated by the control analysis, that these two latter differences could not result from biomechanical distortions that might have caused artifactual modifications in the spatial characteristics of the UF movements.

From a theoretical point of view, none of the previous differences would have been expected if compliant and unconstrained movements involve the same underlying control strategies. Note that the differences we observed between compliant and unconstrained movements could provide a way to resolve some apparently contradictory results reported in the movement generation literature. In particular, as in the experiments studying unconstrained movements (Atkeson and Hollerbach 1985; Haggard and Richardson 1996; Lacquaniti et al. 1986), we observed consistently curved hand paths in the U condition. At the same time, as in the experiments dealing with compliant motions, we observed roughly straight-line paths (Flash and Hogan 1985; Morasso 1981) and characteristically elongated endpoint distributions (Gordon et al. 1994) in the C condition.

Instruction to perform straight movements modifies the characteristics of the unconstrained movements, but not those of the compliant movements

Interestingly, the instruction to follow a straight-line path affected the spatiotemporal characteristics of the unconstrained movements only. Such a selective influence would not have been expected if compliant and unconstrained movements involve the same planning processes. The large differences observed between the UF and US conditions suggest that the unconstrained movements were, unlike the compliant movements, not programmed to follow a straight-line path. This conclusion is supported by the results of the control analysis, which showed that the differences observed between US and UF for both the path curvature and the endpoint distribution shape could not be related to movement velocity, i.e., to biomechanical factors (Flash 1987). It is also indirectly corroborated by a pioneering study of Lacquaniti et al. (1986), who showed that the kinematic and dynamic characteristics of U movements, directed toward the body, were fundamentally modified when a mechanical device compelled the subjects to move the hand along a straight-line path.

It might be hypothesized that the differences observed between the UF and US conditions were the result of attentional processes, the subjects being more careful when
required to follow a straight path. This hypothesis is implausible, however, considering in particular the differences between the characteristics of the UF and US endpoint distributions: if the UF and US conditions had involved the same planning process, the endpoint distributions, which are assumed to reflect the random variability in neural processing (Flanders et al. 1992; Gordon et al. 1994), should have been isomorphic in these two conditions. Another indirect argument supporting the hypothesis that the differences observed between UF and US were not related to attentional factors can be drawn from the absence of differences observed between the CF and CS conditions.

Target eccentricity influences selectively the curvature of the unconstrained movements

Target eccentricity, which did not influence the path curvature of compliant movements, induced significant variations of the degree of curvature of the UF movements. Considering that the variations observed in UF were not related to biomechanical distortions, the selective action of the eccentricity factor on this condition would not have been expected if the compliant and unconstrained movements involved the same underlying control strategies.

In summary, the results of the present study suggest that compliant and unconstrained movements involve different control strategies. Although the description of these different strategies is beyond the scope of the present study, some remarks can be made.

CONSTRANDED MOVEMENTS. The path shape invariance observed with respect to the experimental conditions strongly favors the hypothesis, already proposed by several investigators, that compliant movements are planned in the extracorporeal space (Flash and Hogan 1985; Morasso 1981). At the same time, the fact that the endpoint distributions were typically elongated in the movement direction can be seen as an indication that this extracorporeal planning involves a separate specification of movement direction and extent (see Gordon et al. 1994 for a detailed discussion of this point).

UNCONSTRAINED MOVEMENTS. Neither the hand path shape nor the endpoint distributions presented invariant characteristics. As suggested by the control experiment, the specific features of the UF movements were not related to biomechanical factors, but to the planning variables used by the CNS to generate the movement. This observation suggests that the straight hand paths, and typically elongated endpoint distributions, observed by several investigators (Flash and Hogan 1985; Gordon et al. 1994; Morasso 1981), might be task specific and related to the execution of compliant movements. Of course, additional experiments are necessary to confirm the validity of this hypothesis, and to determine whether the differences observed between the compliant and unconstrained movements are underlain by similar or distinct neural processes. The answer to this question might be crucial as regards the interpretation and theoretical implications of many neurophysiological studies dealing with compliant motions.

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