

TR - H - 069

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for Trajectory Curvature in
Multi-Joint Arm Movements**

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1994. 3. 31

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Examinations of Possible Explanations for Trajectory Curvature in Multi-Joint Arm Movements

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Abstract

Although the straightness of hand paths is a widely accepted feature of human multi-joint reaching movements, detailed examinations have revealed slight curvatures in some regions of the workspace. A question therefore arises as to whether planned trajectories are straight or curved. If they are in fact straight, at least three possible factors can explain the observed curvatures: (1) Imperfect control, (2) Visual perceptual distortion, or (3) Interaction between straight virtual trajectories and the dynamics of the arm. However, these three factors are not exhaustive, just the likeliest candidates. Nonetheless, rejecting them is equivalent to saying that planned trajectories themselves are likely to be curved. In Experiment 1, subjects instructed to generate straight movement paths from the side of the body to the front, produced much straighter movements than those generated spontaneously; this argues against (1). In Experiment 2, subjects generated spontaneously curved trajectories in the fronto-parallel plane where visual perceptual distortion was not expected; this argues against (2). In Experiment 3, EMG signals of six related muscles suggested that subjects generated straighter paths without increase in arm stiffness; this argues against (3). It thus follows that planned trajectories are likely to be curved. Because there is no theoretical reason to plan curved trajectories in extrinsic space, we conclude that trajectories are planned in intrinsic space while taking into account the dynamics of the musculoskeletal system.

Introduction

Recent studies have demonstrated a common kinematic feature of visually-guided, planar multi-joint human arm movements: when the initial and final positions of such movements are given, the trajectories tend to be roughly straight and smooth, and display bell-shaped tangential velocity profiles (Kelso, Southard, & Goodman, 1979; Morasso, 1981; Abend, Bizzi, & Morasso, 1982; Flash & Hogan, 1985; Uno, Kawato, & Suzuki, 1989). Some others have demonstrated that when the fine details of such roughly straight trajectories are examined, the trajectories seem to be gently curved in some regions of the workspace. Actually, it turns out that movements within the same region of the workspace are quite similar to one another, but differ from those produced in other regions of the workspace. In the horizontal plane at the shoulder level, transverse movements were found to be curved outwardly convex but radial movements were relatively straight (Uno, Kawato & Suzuki, 1989; Haggard & Richardson, 1993). In the vertical plane, up and down movements were found to be outwardly convex while back and forth movements were relatively straight (Atkeson & Hollerbach, 1985). Thus, it appears that the detailed features of trajectories depend on the workspace region in which the movement is executed.

There are two ways to control movements: feedforward control and feedback control. Bizzi, Accornero, Chapple, & Hogan (1984) demonstrated the existence of a feedforward control mechanism in the monkey's arm. In their experiments, deafferented monkeys could execute reaching movements without visual information. This shows that movements can be executed by pure feedforward control because feedback control is impossible under such condition. When the forearm position of the deafferented monkey was perturbed during the reaching

movement, the arm returned to a position characterized as intermediate between the initial and target positions before moving back to the target position. This suggests that not the final position only, but the whole trajectories are planned in the CNS. Feedback control will be enough to execute rather slow movements, but feedforward control seems to be indispensable for relatively fast movements because the long delay of neural feedback loops makes purely feedback control systems unstable for such movements (Katayama & Kawato, 1993). Thus, one may well say that the ballistic components of reaching movements are planned beforehand in the CNS. Then, the question arises as to whether the planned trajectories themselves are curved or whether the planned trajectories are straight but the realized trajectories are curved for some reason.

It has been widely accepted that the trajectories are planned in the workspace because this allows the external constraints to be most easily captured (Flash & Hogan, 1985). Planning in another, more intrinsic space, such as a joint space or muscle space, is widely regarded as rather implausible because the observed straightness of the trajectories is difficult to be reproduced. Assuming that the CNS plans straight paths as the virtual trajectories, Flash (1987) attributed the deviation from the planned straight trajectories to the interaction between virtual trajectories and dynamics of the arm. Such deviation may occur depending on the workspace region.

However, recent studies (Uno, Kawato, & Suzuki, 1989; Uno, Suzuki, & Kawato, 1989; Dorney, Uno, Kawato, & Suzuki, 1995) have demonstrated that planning in intrinsic space can reproduce roughly straight human trajectories when the dynamics of the musculoskeletal system are taken into account. These studies predict trajectories that deviate slightly from a straight line depending on the area of the

workspace, and the predictions are in good accordance with the observed trajectories. Uno, Kawato, & Suzuki (1989) advocate that the planned trajectory itself is curved because it is planned using variables other than in kinematic, Cartesian coordinates. The purpose of the present set of studies was to bring to conclusion which of these two interpretations was plausible through behavioral experiments.

Indeterminacy Problem

In reaching from one point to another, there is an infinite number of possible hand trajectories. These trajectories can either be straight, very curved or somewhere in between. Here, even when the shape of the paths is determined, there is an infinite number of possible time profiles of the movements. The invariant feature of human hand trajectories suggests that the CNS decides on one desired trajectory among all of the possible trajectories. Some mechanism selects one trajectory and reject others. This is called an indeterminacy problem in the sense that the solution is not unique.

A number of approaches have been proposed to explain how humans solve such problems. Some of these approaches have utilized a mechanism to reduce the number of degrees of freedom in the motor control system. For example, Bernstein (1967) proposed that there are synergies among muscle groups that help reduce the number of degrees of freedom to be managed. The task dynamics approach proposed by Saltzman & Kelso (1987) also provides specific principles to introduce couplings between the high-level task space, the low-level body space and the motor command space.

In engineering, an objective function is frequently used to select a unique solution for a problem. This optimal control concept was also explored in biological motor control. In order to explain the features of

human reaching movements, various optimization principles have been examined. The objective function is chosen to quantitatively evaluate the performance of the system under control. This objective function is usually defined as the integral of an instantaneous cost over a movement time interval. Of course, the goal is to minimize the value of this objective function. Nelson (1983), for one, examined objective functions related to movement time, distance, peak velocity, energy, peak acceleration and the rate of change of acceleration (jerk). In reaching movements, smoothness (in the sense of the third time derivative of the position (jerk)) seems to be the lowest possible order of the performance index which accounts for the major features of human movements. The lower order performance indices that predict large discontinuities in acceleration are rejected from experimental data (Kawato, 1995).

Planning Space

In order to execute feedforward control, planning processes must solve the indeterminacy problem and select a unique trajectory which captures the external constraints, such as targets or obstacles. Although the targets or the obstacles of movements are usually given in the external visual space, it does not necessarily mean that the planning must also be executed in the extrinsic space. It is possible to provide the necessary constraints to solve the indeterminacy problem in an intrinsic, body space such as a joint angle space, torque space or motor command space. Models are classified by whether the planning space is extrinsic or intrinsic. It is also possible to differentiate models according to whether their planning relies only on the kinematic aspect of the movements, or whether they also take into account the dynamic property of the musculoskeletal system and of the interacting environment. In kinematic planning, a change in the external force causes no change in planned

trajectories although it may change the actual trajectories. On the other hand, if the dynamic property is taken into account, a change in the external force must influence the trajectory planning. These two methods of classification, that is, extrinsic vs. intrinsic and kinematic vs. dynamic, lead to four possible candidate types ('extrinsic-kinematic', 'extrinsic-dynamic', 'intrinsic-kinematic', and 'intrinsic-dynamic'). There is a group of models incapable of being precisely classified into one of these four categories, and it is called the virtual trajectory control hypothesis or equilibrium-point hypothesis. These models plan motor commands, which are the intrinsic variables, based on the extrinsic coordinates. See Figure 1.

	Kinematic	Dynamic
Intrinsic	straightness in joint angle space straightness in muscle length space	minimum-torque-change minimum-muscle-tension-change minimum-motor-command-change
Intrinsic planning based on extrinsic coordinates minimum-jerk virtual trajectory straight shift of the hand EP (lambda model)		
Extrinsic	minimum-jerk model Jordan et al.'s model task-dynamics ----- (visual space) minimum-jerk in visual space	(jelly-jolting version of minimum-jerk model)

Figure 1. Classification of the models.

Planning in Extrinsic Space

The minimum-jerk model proposed by Flash & Hogan (1985) can be classified as an extrinsic-kinematic planning model. It predicts purely

straight trajectories in Cartesian space. This minimum-jerk model was the first optimization model of multi-joint movements capable of being experimentally confirmed. The objective function of this model is given by:

$$C_J = \frac{1}{2} \int_0^{t_f} \left\{ \left(\frac{d^3 X}{dt^3} \right)^2 + \left(\frac{d^3 Y}{dt^3} \right)^2 \right\} dt$$

where (X, Y) are the Cartesian coordinate of the hand, and t_f is the movement duration. In the minimum jerk model, the optimal solution for a point-to-point movement depends only on the geometric relationship between the initial and final points: in other words, the minimum jerk trajectory is independent of the dynamics of the musculoskeletal system. Thus, the minimum jerk model implies that the trajectory is first planned in extrinsic space, independent of the motor control in intrinsic space. Then, it is translated as required into the appropriate motor command.

Wolpert et al. (1994) argued that trajectories are planned in a distorted, visually perceived space rather than in real Cartesian space. They stated that the planned trajectories are straight as minimum-jerk trajectories in the visual space but are possibly curved in the real Cartesian space because visual perceptual distortion exists.

Considering the dynamic property of the musculoskeletal system, planning processes may not need to perfectly solve an indeterminacy problem but biomechanical constraints can help determine the unique trajectory. The model proposed by Jordan, Flash, & Arnon (1993) may be one such model. In their model, the spatial aspects of movements are planned in extrinsic space, e.g., the straightness of the paths, whereas the temporal aspects, e.g., bell-shaped velocity profiles, are given as the results of the implicit smoothing properties of the dynamical systems underlying the movements.

The task-dynamics approach proposed by Saltzman & Kelso (1987), although not an optimization approach, may be classified as an extrinsic model. It assumes that abstract simple dynamics in the task space solve the indeterminacy problem. The task-space dynamics are transformed into joint angle space dynamics. This model plans a straight trajectory in extrinsic space and, according to the control schema, a straight or quasi-straight trajectory is expected to be generated.

Is it possible to construct models that can be classified as extrinsic-dynamic planning models in the sense that they take into account the dynamic property of the system at the extrinsic planning level? We may express the biomechanics of the system in terms of a dynamic property of the hand (end-point) in extrinsic, workspace coordinates, such as the apparent hand inertia or hand stiffness. We may plan the trajectory depending on the end-point dynamics. The visco-elastic model proposed by Wann et al. (Wann, Nimmo-Smith, & Wing, 1988) may be interpreted as aiming at such a model. Considering the difference between an individual's perception of "jerkiness" and the mean-squared hand jerk as used by Flash & Hogan (1985), they assumed that humans move the hand in such a way as they "feel smooth". This idea led to their concept of the perceptual center, which is the center of mass of the visco-elastic bodies related to the dynamics of the tissue. However, because they assumed that the dynamics of the tissue can be adequately approximated by a linear second-order system, the perceptual center does not precisely reflect the nonlinear dynamics of the musculoskeletal system. Hogan (1985) showed that end-point dynamics have directional properties which depend strongly on the location of the end-point in the workspace. In other words, end-point dynamics highly depend on the intrinsic variables; this contradicts the concept of extrinsic-dynamic planning. Generally speaking, it is impossible to precisely model the end-point dynamics in

extrinsic space because of the existing kinematic and dynamic redundancies. Hogan (1985) also showed that the end-point dynamics can be modified by using an excessive degree of freedom. Thus, a true extrinsic-dynamic planning model capable of precisely reproducing the observed hand trajectories seems impossible.

Intrinsic Planning Based on Extrinsic Coordinates

The minimum-jerk model does not specify its control mechanism. This model only specifies the trajectory to be satisfied. The planned straight hand trajectories may be executed by directly solving an inverse kinematics and inverse dynamics problem or by some other way. One way to avoid a complicated inverse calculation is to utilize servo control mechanisms. Flash (1987) combined the minimum-jerk model with a servo control model called the virtual trajectory control hypothesis (Bizzi, Accornero, Chapple, & Hogan, 1984; Hogan, 1984). In the virtual trajectory control hypothesis, the required joint torques are each generated as the product of the mechanical stiffness and the difference between the virtual and real trajectories. The virtual trajectory, and not the real trajectory, is assumed to have been planned as the minimum-jerk trajectory.

The equilibrium-point hypothesis proposed by Feldman (1966a, 1966b, 1986), which is another servo control model, utilizes the feedback properties of stretch reflexes. In his model, the equilibrium-point of the hand shifts in a straight line toward the target. The equilibrium-point specifies the motor command λ , which is the threshold of the stretch reflexes. The model expects curvature in the hand paths and hooks at the end of the movements.

In both cases, the planning of the virtual trajectories is done purely in extrinsic space. These planned trajectories specify the motor command

sequence, that is, the intrinsic control variables, and the dynamics of the musculoskeletal system and spinal reflex loops cause deviations of the realized trajectories from the planned trajectories. That is, although the virtual trajectory is straight, the real trajectory is slightly curved. As the speed of movement increases, the limb's inertia and viscosity are expected to cause larger deviations from the virtual trajectory. In order to reproduce a roughly straight movement from the straight virtual trajectory, a relatively high stiffness must be assumed for faster movements.

According to recent measurements (Gomi, Koike, & Kawato, 1992; Bennett, 1993; Gomi & Kawato, 1995), the stiffness during movement is much lower than that assumed in Flash's simulation (Flash, 1987). If the measured dynamic stiffness values during movements are used, the real multi-joint trajectories are overly curved and do not even come close to the target points (Katayama & Kawato 1993). McIntyre & Bizzi (1993) also suggested that straight-path virtual trajectories cannot adequately account for the known behaviors of even single joint (elbow) movements. Considering these results, it would seem difficult to assume that straight virtual trajectories are used to control arm movements.

Planning in Intrinsic Space

In the intrinsic category, we can think of several different spaces: joint angle, muscle length, torque, muscle-tension and motor-command. Among them, planning in the joint angle space and muscle length space can be classified as intrinsic and kinematic. The other three are classified as intrinsic and dynamic. As pointed out by Hollerbach (1990), a straight trajectory in joint angle coordinates yields a complex trajectory in endpoint Cartesian coordinates, and cannot account for roughly straight hand trajectories in front of the body. This eliminates the plausibility of

straight path planning in joint angle space. Muscle length may safely be assumed to roughly have a linear relationship with joint angle except at the end of the workspace region (Winters, 1990). This means that straight trajectory in muscle length space is likely to be approximately straight in joint angle space and, as a result, overly curved in hand space. Thus, straight path planning in muscle length space also seems to be implausible.

With respect to planning in intrinsic-dynamic space, several models have been proposed: the minimum-torque-change model, the minimum-muscle-tension-change model and the minimum-motor-command-change model. Uno, Kawato, & Suzuki (1989) simulated the minimum-torque-change model using estimated physical parameters and found that it can reconstruct gently curved hand trajectories. Uno, Suzuki, & Kawato (1989) then extended the minimum-torque-change model to the minimum-muscle-tension-change model for several reasons. One reason was that the musculoskeletal system possesses muscle-tension sensors (Golgi tendon organs) as well as muscle-length and velocity sensors (muscle spindles) but no direct joint-torque sensors. The minimum-muscle-tension-change model also predicts curved trajectories similar to actual trajectories. Dornay, Uno, Kawato, & Suzuki (1995) came to similar conclusions while using a monkey's arm model derived from anatomical measurements. Kawato (1992) has proposed extending this model to one that he calls the minimum-motor-command-change model on theoretical grounds. The objective function of the minimum-motor-command-change model is given by:

$$C_M = \frac{1}{2} \int_0^{t_f} \sum_{i=1}^n \left(\frac{dM_i}{dt} \right)^2 dt$$

where M_i is the i -th motor command out of n . Planning trajectories

according to one of these dynamic optimization principles necessitates the use of internal models of the controlled object and an explicit solution to the inverse kinematics and inverse dynamics. The motor command or muscle tension can be obtained directly from the constraints of the movements (targets, via-points, etc.) represented in task-oriented coordinates by utilizing the internal models (Uno, Kawato, & Suzuki, 1989).

Let us summarize various classes of trajectory planning models depicted in Figure 1. An extrinsic-kinematic model, especially the minimum-jerk model, is an attractive candidate as a trajectory planning model for the human arm. In particular, the minimum-jerk model combined with the virtual trajectory control hypothesis seems to be a computationally less demanding model capable of explaining multi-joint arm movements without assuming a complicated calculation, although it assumes a higher level of stiffness than the experimental data. Yet, no experimentally confirmable extrinsic-dynamic model in the strict sense of the word has been constructed. Such models seem to be implausible, because the biomechanical system cannot be uniquely described in extrinsic space. Straight planning with an intrinsic-kinematic model, such as the angular-jerk-minimum model or planning in muscle length space, is rejected on experimental grounds. In contrast, intrinsic-dynamic models are another type of plausible models capable of explaining the trajectory curvature depending on the workspace region although they need internal models of the dynamics and kinematics.

Thus, we focus on models that rely on extrinsic-kinematic planning and models that rely on intrinsic-dynamic planning.

Explanations for Curved Trajectories and Logic of Experimental Design

If the CNS plans a straight trajectory in extrinsic space, there must be some reason in the processes other than planning that can explain the observed curvature in actual trajectories. If the CNS plans a desired trajectory in intrinsic space, however, the major reason for the curvature can be attributed to a curvature at the planning level.

Wolpert et al. (1994) listed four possible explanations for the curvature of point-to-point movements.

1. The desired trajectories are straight but the imperfection of control causes the curvature.
2. Visual perceptual distortion contributes to the curvature.
3. The desired trajectories are given as virtual trajectories and the interaction between straight virtual trajectories and the dynamics of the arm causes the curvature.
4. The desired trajectories themselves are curved because they are planned in intrinsic space.

The first three explanations are for planning in extrinsic space. The first one is that the CNS tries to generate trajectories that perfectly fit the plan by a certain control mechanism but the imperfect control mechanism prevents the hand from generating perfectly straight trajectories. The second one is based on the well-known phenomenon that a visually perceived (apparent) fronto-parallel plane is skewed compared to the real fronto-parallel plane (Foley, 1980). That is, at the distances near to the observer the fronto-parallel plane appears convex towards the body, but at the far distances it appears concave away from the body. If the trajectories are planned in a visually perceived space rather than in real Cartesian space, the optimal trajectories must be straight in the visually

perceived space, and, as a consequence, curved in the real Cartesian space. Wolpert et al. (1994), who advocate extrinsic planning, experimentally supported the contribution of the second factor. The third explanation is based on the virtual trajectory control hypothesis.

Regarding the fourth explanation, if the desired trajectories themselves are curved, it does not necessarily mean that the trajectories are planned in intrinsic space: it only means that the planned trajectories are curved for some reason. However, optimization models in extrinsic-kinematic space, such as the minimum-jerk model, predict perfectly straight paths for point-to-point movements. This is because any kinematic model with symmetry predicts an invariant objective function value under translation, rotation or reflection: thus, curved paths can not be unique optimal solutions. There seems to be no known plausible reason at present to assume an asymmetric model in kinematic space. If a curved path were the unique optimal solution, the symmetrically reflected curved path with respect to the line connecting the starting and end points should have exactly the same objective function value, and thus should become another unique optimal solution. From such a contradiction it follows that optimal trajectories in a kinematic optimization model with symmetry must be straight. Thus, the most appropriate explanation for curved trajectories in extrinsic space is that they are planned in a space other than extrinsic space, such as intrinsic space.

The first three factors are the likeliest ones capable of explaining the curvature in extrinsic planning although they may neither exhaustive nor exclusive. If these three explanations can be refuted, we may well say that planned trajectories themselves are likely to be curved. This would lead us to conclude that trajectories are planned in intrinsic space taking into account the dynamics of the musculoskeletal system (fourth explanation). In this study, we test the first three explanations.

Imperfection of Control (the first explanation)

To test the first explanation, we assumed that if the CNS prefers straight hand trajectories in point-to-point movements, then the CNS will try to do almost the same thing as when it is explicitly asked to generate straight hand trajectories. Of course, some difference may exist between the two conditions, such as whether the subject is conscious or unconscious about the path constraints or how rigidly he tries to satisfy the path constraints. However, if the imperfection of control causes the curvature, the trajectories generated under each condition, namely, the spontaneous movement and the movement instructed to be straight, should be similar. That is, if we ask subjects explicitly to make straight trajectories in regions where "natural" trajectories tend to curve, the subjects should be unable to generate or have difficulty generating straight, or even straighter trajectories than spontaneously curved point-to-point movements. In order to make straight trajectories, in this case, the subjects must improve their control process. On the contrary, if the CNS plans trajectories in intrinsic space, its attempts at spontaneous point-to-point movements should be different from those when it is explicitly asked to generate straight hand trajectories. In this case, the trajectories generated under each condition will possibly be quite different from the others. If a subject can generate a straighter trajectory than the spontaneously curved one when asked to do so, we can reject the first explanation.

Visual perceptual distortion (the second explanation)

There is no doubt that visual information is important for trajectory planning in reaching movements. Wolpert et al. (1994) were the first to address the effect of the visual misperception of curvature on the planning of trajectories (the second explanation). Their results showed a highly

significant linear relationship between the perceived curvature and the movement curvature. Their conclusion was that the desired hand trajectory of subjects is straight but that visual perceptual distortion contributes to the curvature of the movement. However, there is no logical necessity to assign causality to such a linear relationship. The underlying assumption of their conclusion was: the trajectory is planned in visual space, that is, the trajectory is planned to appear straight. This assumption and the observed linearity led them to conclude that perceptual distortion causes the distortion of the planned trajectory. If perceptual distortion is the main reason for the curvature, however, no or little curvature should be expected in places with no perceptual distortion. If the movement curvature is observed when the subjects are able to perceive the curvature correctly, we have to assign another reason for the curvature. Thus, to test the second explanation, we first have to examine the structure of the visual space to find a place where there is no perceptual distortion. Extensive studies on the visual space will answer this question.

There is no a priori reason that forces the visual space as a whole to be structured as Euclidean. Luneburg (1947), who discussed the geometry of the visual space, concluded that this space is a hyperbolic space of constant curvature. Rods on the horizontal plane which appears to lie parallel to the fronto-parallel plane are convex to the body at a far distance and are concave to the body at a near distance (apparent fronto-parallel plane, AFPP. Foley, 1980). They are straight only at the distance where the concavity changes to convexity. Indow & Watanabe (1988) estimated the Gaussian curvature K of the visual space by using the conventional method of measuring the discrepancy between alleys that appear parallel (parallel alleys) and alleys that appear equal in lateral separation (equidistant alleys). The sign of the Gaussian curvature K

indicates the property of the space: elliptic ($K > 0$), Euclidean ($K = 0$), or hyperbolic ($K < 0$). Their conclusion was that the perceived horizontal plane at eye-level is structured according to hyperbolic geometry, whereas fronto-parallel planes, or surfaces perpendicular to the line of sight are structured according to Euclidean geometry. These findings tell us that a line appearing straight in three-dimensional space also appears straight when projected onto the fronto-parallel plane, although it may be curved when projected onto the horizontal plane. The points in the fronto-parallel plane which appear to lie on a horizontal line at eye-level do not appear to be either upward convex or downward convex.

Wolpert et al. (1994)'s finding of convex cursor movements in the transverse direction being perceived as straight was in accord with the static AFPP results. If the misperception of the cursor movements is the effect of the geometrical property of the visual field, the misperception is expected only in movements on the horizontal plane. There will be no contribution of misperception for the curvature of movement on the fronto-parallel plane.

To investigate see whether visual perceptual distortion can be observed for cursor movements on the fronto-parallel plane, an informal experiment was executed using the first author as a subject. A two-alternative forced choice paradigm assessed the subject's ability to judge the curvature of a cursor movement. The cursor was displayed on a CRT screen, whose surface was aligned parallel to the fronto-parallel plane of the subject. The subject observed the cursor making a 1 sec horizontal minimum-jerk trajectory at the level of the eyes. The distance from the CRT display to the subject's eyes was about 30 cm. The cursor moved from right to left. The distance between the initial cursor position and final cursor position was 250 mm (visual angle of about 48°). By adding a semisinusoid of variable amplitude to the straight trajectory for each

movement, the path was curved either downward or upward from the straight line. A negative sign was given to the amplitude of a semisinusoid producing a downward curvature, and vice versa. We tested 21 different amplitudes ranging evenly from -10 mm to 10 mm (visual angle of about -2° to 2°). The data was analyzed using probit analysis; a cumulative Gaussian function was fitted to the forced choice data to calculate the mean, that is, the amplitude of the sinusoid at which the subject perceived the cursor as moving in a straight path. The 95% confidence limit of the mean was estimated from a psychometric function. The mean was -0.20 mm (visual angle of about $-2'$), its lower limit was -0.63 mm (visual angle of about $-7'$), and its upper limit was 0.24 mm (visual angle of about $3'$) (See Figure 9). As the interval of the 95% confidence limit was rather small and included a straight path, that is, the amplitude of 0 mm, we thought it was possible to conclude that the actual path of the cursor perceived as moving in a straight path was in fact straight. Therefore, there seems to be no distortion in the visual perception of curvature in horizontal movements within the fronto-parallel plane.

Minimum-jerk Virtual Trajectory (the third explanation)

First of all, as mentioned in the previous section, control by a straight virtual trajectory itself is now in doubt. In the present study, we examined whether observations were possible that contradict the virtual trajectory control hypothesis.

In the virtual trajectory control hypothesis, the required joint torques are each generated as the product of the mechanical stiffness and the difference between the virtual and real trajectories. If the stiffness is high, the real trajectories are likely to be close to the virtual trajectories, but if the stiffness is low, the real trajectories are likely to be curved

because of biomechanics. In order to generate trajectories straighter than spontaneously curved ones using the same minimum-jerk virtual trajectory as that used in the spontaneously curved movements, the value of the stiffness must be increased.

The stiffness can be increased either by raising the muscle inherent mechanical stiffness by co-activation or by raising the reflex gain. Mussa-Ivaldi, Hogan, & Bizzi (1985) measured the static hand stiffness of a multi-joint posture and represented it as an ellipse. The stiffness in a given posture is changeable in terms of magnitude but is unchangeable in terms of orientation (direction of the maximum stiffness) and shape (the ratio of maximum to minimum stiffness). This means that the descending command which activates the agonist and antagonist muscles will be raised with the same ratio, and/or, the reflex gain of the agonist and antagonist muscles will be changed with the same ratio. In both cases, the activation of both the agonist and antagonist will be different from those of movements using the same straight virtual trajectory under lower stiffness. If the stiffness is increased by muscular co-activation, the activation of both the agonist and antagonist muscles must be increased at the same time. In contrast, if the stiffness is increased by raising the reflex gain, the activation of the agonist at the beginning of the movements must be raised, whereas the activation of the antagonist at the end of the movements must be raised to stop the movements.

Thus, we can see whether the minimum-jerk virtual trajectories are used in both spontaneous and instructed straight movements by examining the activation of the muscles measured as EMG signals. There is another possible strategy of changing the virtual trajectories themselves for straighter movements, and it will be considered later in the Discussion.

Overview of Present Experiments

We executed the following experiments to test the plausibility of the three explanations based on planning in extrinsic space. In Experiment 1, we focused on path differences in order to test the first possibility, i.e., that the desired trajectories are straight but the imperfection of control causes the curvature. Movements from the side of the body to the front of the body were selected because they were reported to have markedly curved trajectories in previous studies by Uno, Kawato, & Suzuki (1989) (see Figure 2a). In Experiment 2, we tested the second possibility, i.e., that visual perceptual distortion causes the curvature. Lateral movements at the level of the subjects' eyes in the fronto-parallel plane were selected because they are not influenced by visual perceptual distortion (see Figure 2b). In Experiment 3, we examined the third possibility, i.e., that the minimum-jerk virtual trajectory causes the curvature. We examined movements that were similar to those in Experiment 1 but strictly constrained them to the horizontal plane at the level of the shoulder. EMG signals were measured to examine the level of co-activation to see whether the stiffness was raised in straighter movements. The whole experimental procedure is shown in Table 1.

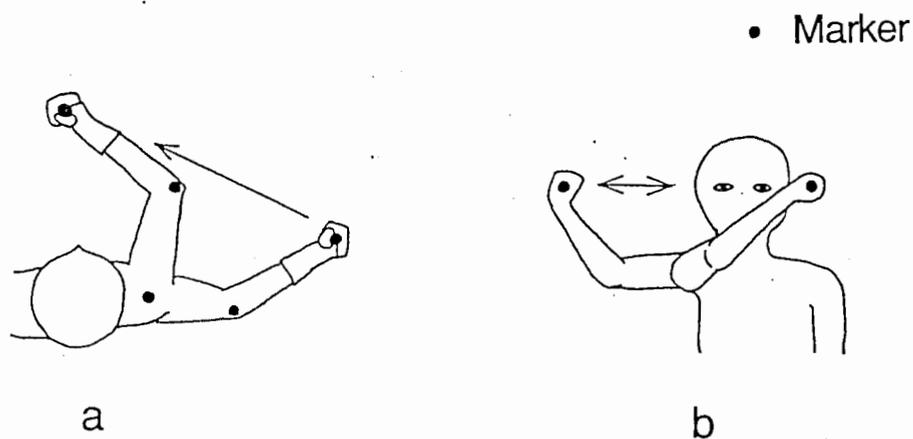


Figure 2. Experimental settings. **a.** Experiments 1 and 3. **b.** Experiment 2.

Table 1. Experimental Procedure

<u>Exp. 1</u>			
instruction	trial number	blocks	test block
1 spontaneous 1st	50	1 - 5	5
2 with curved guidance 1st	40	6 - 9	9
3 instructed straight 1st	50	10 - 14	14
4 with straight guidance	80	15 - 22	22
3 instructed straight 2nd	100	23 - 32	32
2 with curved guidance 2nd	40	33 - 36	36
1 spontaneous 2nd	40	37 - 40	40

<u>Exp. 2</u>			
instruction	trial number	blocks	test block
1 spontaneous, left to right	20	1 - 2	2
1 spontaneous, right to left	20	3 - 4	4
3 instructed straight, left to right	30	5 - 7	7
3 instructed straight, right to left	30	8 - 10	10
1 spontaneous, left to right	20	11 - 12	
1 spontaneous, right to left	20	13 - 14	

<u>Exp. 3</u>			
instruction	trial number	blocks	test block
1 spontaneous	30	1 - 3	
3 instructed straight	30	4 - 6	
4 with the straight reference	30	7 - 9	
4 with the straight reference	30	10 - 12	
3 instructed straight	30	13 - 15	15
1 spontaneous	30	16 - 18	18

Experiment 1

Method

Subjects

Four right-handed naive subjects, aged from 20 to 28 participated in this study.

Apparatus

The subjects were seated on a chair with their shoulders fixed to the back of the chair by a harness and their wrists braced. The targets of the movements were set on a horizontal table kept a little below the shoulder

level. The subjects grasped a laser pointer (with their right hand) attached vertically to the brace. In order to make relatively unconstrained horizontal movements, they were asked to keep their hand a little above the table and point the laser beam at the targets. The positions of the hand, elbow and shoulder of each subject were recorded at 400 Hz using the OPTOTRAK position sensing system.

The subjects were also asked to start and stop their hand synchronously with beeps presented at 900 msec intervals to keep the movement duration roughly equal.

Procedure

The initial and final positions of the hand were defined according to the angular positions of the subjects' shoulder and elbow joints (see Figure 2a). The shoulder and elbow joint angles for the initial position were about -3 deg. and 30 deg., respectively, where the arm was to the side of the body. The joint angles for the final position were about 70 deg. and 40 deg., respectively, where the arm was in front of the body. The subjects were asked to move their hand from the initial position to the final position in the horizontal plane.

The following four types of instructions were given to the subjects.

1. Move your right hand from the starting point to the end point.
2. Move your right hand from the starting point to the end point along the curved path drawn on the table (this path is actually the average path of the last 10-trial block of movements performed under instruction 1).
3. Move your right hand straight from the starting point to the end point.

4. Move your right hand along the straight path drawn on the table from the starting point to the end point.

The above four instructions were used to define a set of four corresponding experimental conditions which were given in the following order: 1-2-3-4-3-2-1. The underlying logic in selecting the four instructions was as follows. In instruction 1, trajectories generated under a natural condition were measured. Trajectories observed under this condition can be considered to be the closest to what the CNS plans as optimal trajectories. Instruction 2 was used to control instruction 4, where it is possible to observe the effect of imposing path constraints on subjects even when the path is actually the average of spontaneously generated ones. Instruction 3 was used to test the second and third explanations. Instruction 4 was used to test the effect of visual perceptual distortion under instructed straight movements by comparing trajectories under instructions 3 and 4, and to test the effect of imperfect control by comparing trajectories under instruction 4 to the start-to-goal straight line. Each condition consisted of several blocks of ten trials each, with short rest periods between every two blocks. Additionally, a rather long rest period was given between the fourth and fifth blocks for condition 4. The number of trials under each condition was as follows; 50 (blocks 1-5) - 40 (6-9) - 50 (10-14) -80 (15-22) -100 (23-32) - 40 (33-36) -40 (37-40). For sufficient learning, the trial number under instruction 4 (blocks 15-22) and the latter half of instruction 3 (blocks 23-32) was rather large. The following blocks were selected as test blocks to be analyzed: blocks 5, 9, 14, 22, 32, 36, and 40. These test blocks were the last ones of each condition. (See the upper table in Table 1.)

Data Analysis

For simplicity we projected three-dimensional movements onto the horizontal table plane to treat them as two-dimensional movements. The origin of the table plane's Cartesian coordinate system was the movements' specified starting point; the X-axis was along the line connecting the starting point and the target end point, and the Y-axis was orthogonal to the start-end line. The X-axis was to the right-hand side of the subjects. The Y-axis was directed forward from the body. Each trial in the test blocks was analyzed in the following ways.

Filtering.

The position data were digitally filtered by a sixth-order Butterworth filter having an upper cutoff frequency of 6 Hz. Derivatives of the position data were calculated by successively applying a three-point local polynomial approximation.

Extraction of the ballistic component of movements.

Generally, goal-directed voluntary movements are divided into two components (Flowers, 1975). The first component, called "ballistic", is a fast, pre-programmed movement that brings the hand into the general area of the target. The second component, called "corrective", comprises a number of adjustments. In order to extract the ballistic component of the movements for the experimental purpose, a two-dimensional curvature was used as a threshold to determine the beginning and end of each movement (0.5 (1/mm)) (Pollick & Ishimura, 1995).

Indices for deviation.

In many cases, deviation of the actual hand path from the start-to-goal straight path was small at the beginning of the movements, increased

in the intermediate part of the movements and then decreased again at the end of the movements. In order to compare the extent of the deviation, we adopted the following two kinds of indices. One was the *whole deviation* during the movements, which was quantified as the area between the actual hand path and the start-to-goal straight path. The other was the *maximum deviation* during the movements, which was quantified as the maximum distance between them.

These two indices were calculated for each trial in the test blocks. A start-to-end straight path was calculated for each trial by using the beginning and end positions determined by the above curvature method. As for blocks 9 and 36, we also calculated for each trial the *whole deviation* and the *maximum deviation* of the actual hand path from the curved reference path.

Averaged hand trajectories.

In order to examine the characteristic of the spatio-temporal pattern of the movements under each condition, we adopted the method of normalization and alignment proposed by Atkeson & Hollerbach (1985). According to this method, all movements, whether curved or straight, show an invariant tangential velocity profile when normalized for speed and distance and properly aligned. By applying this method to trajectories within each block and then averaging them within each block, we were able to extract an invariant spatio-temporal pattern of the movements under each condition. See Appendix A for a more detailed explanation.

Results

Figure 3 shows the averaged hand paths and their standard deviation for each test block and each subject. The point (0,0) in each plot denotes

the initial position of the movements. The cross denotes the average X-Y positions normalized and re-sampled at 80 Hz. The orientation of the long axis of an ellipse surrounding a cross denotes the direction of the principal component of the position variation at that time. The radius of this ellipse denotes the standard deviation of the position at that time. The upper plot for each subject shows movements without a visual reference. Among the three curves in the upper plot, from the top are movements spontaneously generated (spontaneously 1st, block 5), instructed straight trajectories before learning (instructed straight 1st, block 14), and instructed straight trajectories after learning (instructed straight 2nd, block 32). The solid lines each denote a start-to-goal straight line. The lower plot for each subject shows movements with a visual reference (with curved guidance 1st, block 9 and with straight guidance, block 22 from the top). The solid lines denote the reference paths under each condition. The spontaneously generated trajectories under instruction 1 (blocks 5 and 40) were remarkably curved outward convexly, while the instructed straight movements were straighter.

Figure 4 shows the average movement time for the first spontaneous movements and in first instructed straight movements. The movement time tended to deviate from 900 msec. The mean and standard deviation for the movement time of all test blocks for each subject were as follows: 858 msec and 97 msec for subject AN, 869 msec and 65 msec for subject NS, 1108 msec and 223 msec for subject KM, and 956 msec and 124 msec for subject SM.

Figure 5 shows the *whole deviation* and the *maximum deviation* for each test block (see above definition). To see the difference, a t-test was carried out on the values of the *whole deviation* for each subject (Table 2).

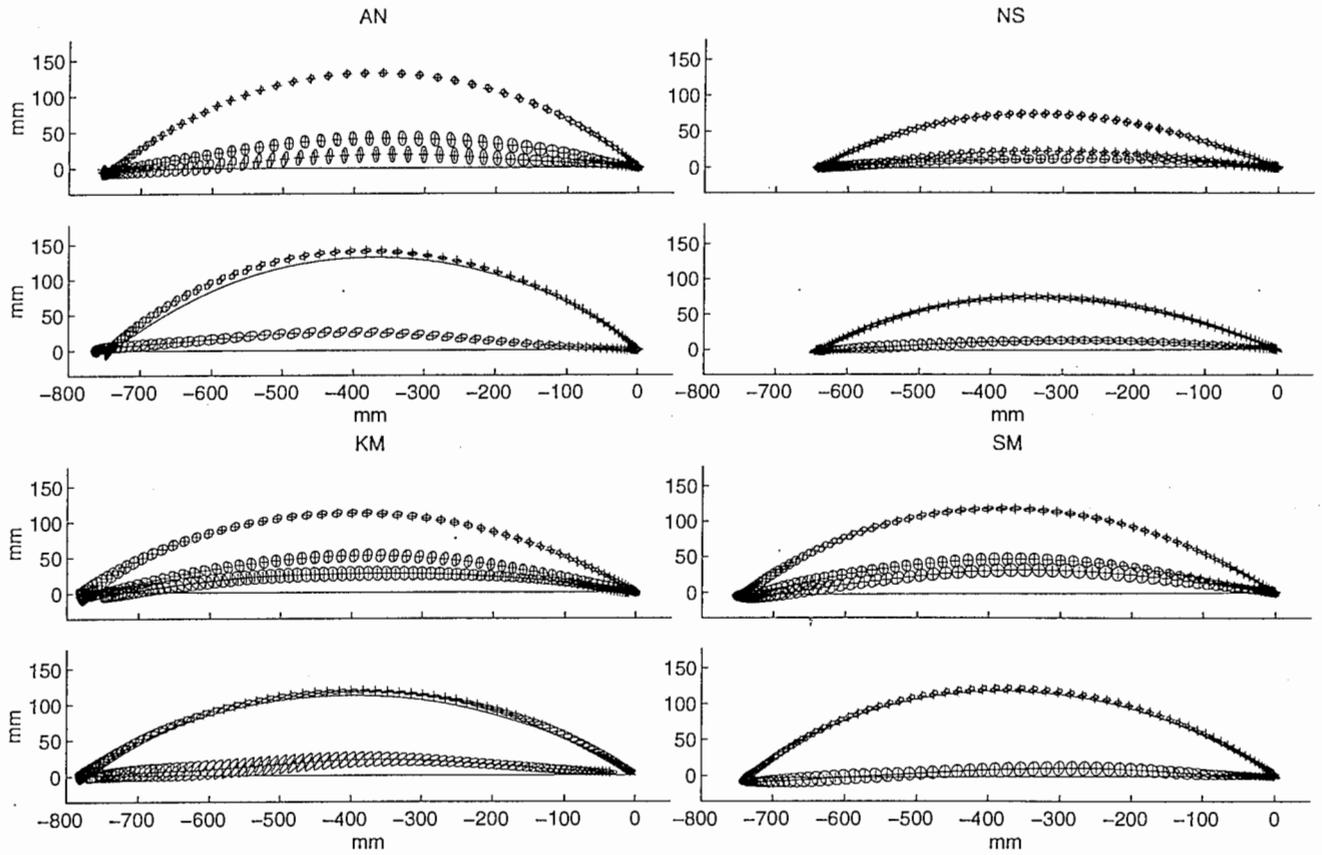


Figure 3. Averaged hand paths and standard deviation for each test block and each subject in Experiment 1. See text for further explanation.

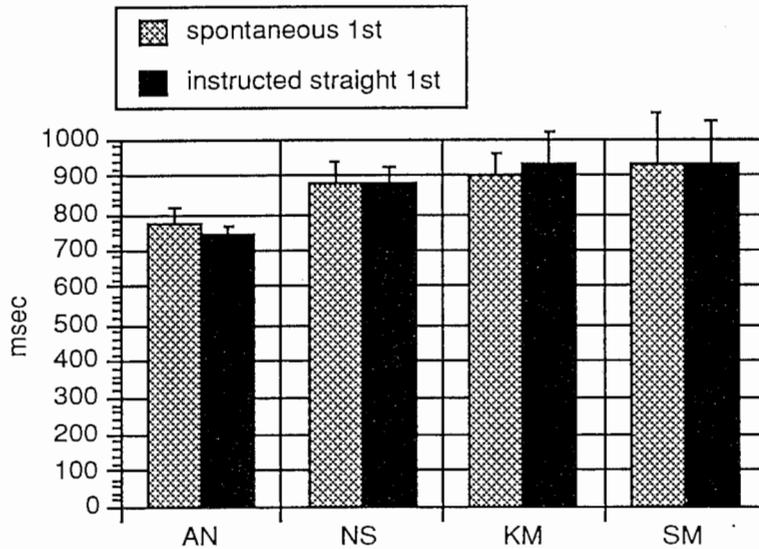


Figure 4. Mean and standard deviation of movement time for the test blocks in the first spontaneous movements and the first instructed straight movements for each subject in Experiment 1.

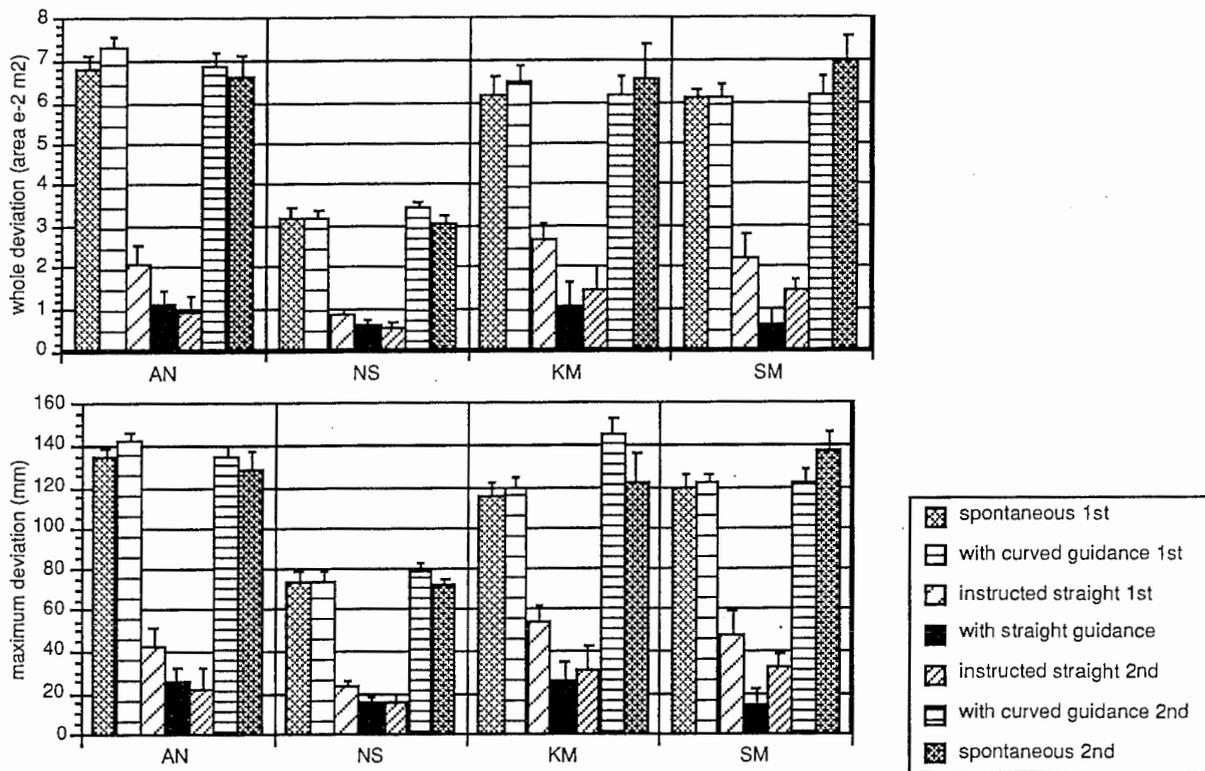


Figure 5. Mean and standard deviation of the *whole deviation* (upper panel) and the *maximum deviation* (lower panel) (see text for definition) for each test block and each subject in Experiment 1.

Table 2. *T-test for the Whole Deviation between Conditions*

block	spontaneous 1st vs. instructed straight 1st		instructed straight 1st vs. with straight guidance		with straight guidance vs. instructed straight 2nd	
	t		t		t	
AN	27.50	**	5.44	**	1.31	n.s.
NS	23.76	**	3.87	**	0.51	n.s.
KM	17.13	**	7.40	**	-1.64	n.s.
SM	18.69	**	7.03	**	-4.68	**

block	spontaneous 1st vs. spontaneous 2nd		instructed straight 1st vs. instructed straight 2nd	
	t		t	
AN	1.16	n.s.	6.15	**
NS	1.34	n.s.	4.48	**
KM	-1.31	n.s.	5.61	**
SM	-5.27	**	3.76	**

*p<.05 **p<.01

The values of the *whole deviation* for the spontaneously curved trajectories (spontaneous 1st, block 5) were significantly larger than those of the instructed straight trajectories before learning (instructed straight 1st, block 14) for all four subjects. The values of the *whole deviation* for the instructed straight trajectories before learning (instructed straight 1st, block 14) were significantly larger than those of the instructed straight trajectories with visual guidance (with straight guidance, block 22) as well as those of the instructed straight trajectories after learning, without a visual reference (instructed straight 2nd, block 32) for all four subjects. These observations showed the effects of learning. The values of the *whole deviation* for the instructed straight trajectories without a visual reference after learning (instructed straight 2nd, block 32) were not significantly different from those with visual guidance (with straight guidance, block 22) for three subjects. The value of the *whole deviation* in block 32 (instructed straight 2nd) for the remaining subject was significantly larger than that in block 22 (with straight guidance), which suggested a decline in performance. These results suggested that the subjects were able to produce straighter trajectories if they were only instructed verbally, and were able to make even straighter trajectories with visual guidance or after they practiced with the visual reference. The values of the *whole deviation* for the spontaneously curved trajectories in the first half (spontaneous 1st, block 5) were not significantly different from those in the second half (spontaneous 2nd, block 40) for three subjects; this suggested the stability of the spontaneous movements.

The visual guidance itself might have somehow caused the curvature observed in the movements with the straight visual reference (with straight guidance, block 22). To test this possibility, we examined the

whole deviation from given the visual guidance in movements with straight guidance and curved visual guidance.

In the trajectories with the curved guidance (blocks 9 and 36), the actual trajectories were significantly different from the reference in three out of eight cases (see Table 3). The constant errors observed in the three cases may be considered as the effect of the visual guidance itself because the reference trajectory was derived from each subject's spontaneous movements. In the trajectories with the straight guidance (block 22), all four subjects were significantly different, that is, outward convex, from the reference. Then, we compared the magnitude of the *whole deviation* from the given guidance between the above two kinds of trajectories. The magnitude was significantly larger for the movements with the straight guidance than for the movements with the curved guidance in seven out of eight cases (see Figure 6 and Table 4).

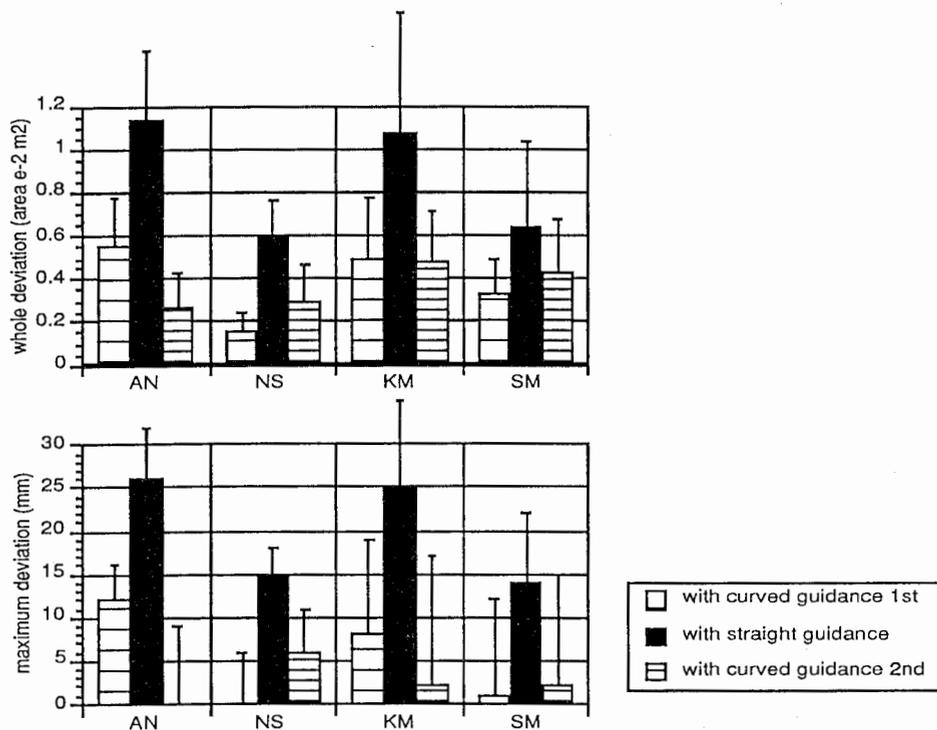


Figure 6. Mean and standard deviation of the *whole deviation* (upper panel) and the *maximum deviation* (lower panel) from visual guidance for the test blocks in the movements with curved and straight visual guidance for each subject in Experiment 1.

Table 3. *T-test for the Difference from the Guidance*

block	with curved guidance 1st	with straight guidance	with curved guidance 2nd	
	t	t	t	
AN	6.37 **	11.37 **	1.07	n.s.
NS	0.67 n.s.	10.25 **	4.35	**
KM	2.95 *	5.88 **	0.93	n.s.
SM	2.13 n.s.	2.94 *	1.70	n.s.

Note. The table denotes whether the paths generated with visual guidance were significantly different from that guidance.

* $p < .05$ ** $p < .01$

Table 4. *T-test for the Whole Deviation from the Guidance between Trajectories with Curved and Straight Visual Guidance*

block	with curved guidance 1st vs. with straight guidance	with curved guidance 2nd vs. with straight guidance
	t	t
AN	-4.71 **	-7.76 **
NS	-6.83 **	-3.74 **
KM	-2.94 **	-3.13 **
SM	-2.74 *	-1.42 n.s.

* $p < .05$ ** $p < .01$

The results in Experiment 1 are summarized as follows. Spontaneously generated movements were remarkably curved outward convexly. When verbally instructed straight, the subjects could generate straighter trajectories. When the visual guidance was given, they could generate even straighter trajectories. They could learn nearly straight movements. However, if the subjects were again asked to move spontaneously, they generated remarkably curved movements.

Experiment 2

Method

Subjects

The same four subjects that participated in Experiment 1 also participated in Experiment 2.

Apparatus

The subjects were seated on a chair with their shoulders fixed to the back of the chair by a harness but this time their wrists were not braced. The two targets of the movements were hung from the ceiling by nylon lines to be in the fronto-parallel plane about 30 cm in front of the subjects' eyes, as well as in the horizontal plane at the level of the eyes. The subjects grasped (with their right hand) a short rod having a position sensor at the end of their little-finger side, and were asked to reach and point to the targets with the rod's end (see Figure 2b for the grip). The recording system and specifications of the movement times were the same as in Experiment 1.

Procedure

The subjects were asked to move their right hand within the fronto-parallel plane though the targets were located in 3-D space. The instructions given to the subjects were those used in conditions 1 (spontaneous) and 3 (instructed straight) from Experiment 1. Both left to right (l-r) and right to left (r-l) movements were examined. The conditions were given in the following order: 1-3-1. Each condition consisted of two groups of 10-trial blocks, with the first group containing l-r trials and the second group containing r-l trials. Short rest periods

were provided between every two blocks. The number of trials in each group was as follows: 20 (l-r) - 20 (r-l) - 30 (l-r) - 30 (r-l) - 20 (l-r) - 20 (r-l). As there seemed to be no qualitative change between the first half and second half of the spontaneously generated movements under instruction 1, we selected as test blocks the last of the first half of the l-r and r-l conditions under instruction 1 and the last of the l-r and r-l conditions under instruction 3. (See the middle table in Table 1.)

Data Analysis

For simplicity we projected three-dimensional movements onto the fronto-parallel plane (X-Z plane) to treat them as two-dimensional movements. Each test block was analyzed in the same way as in Experiment 1.

Results

Figure 7 shows the averaged hand paths and their standard deviation for each test block and each subject, as seen across from the subject. The origins denote the initial positions of the movements. The crosses and ellipses are the same as those in Figure 3 for Experiment 1.

Figure 8 shows the *whole deviation* and the *maximum deviation* in each test block. To see the difference, a t-test was carried out on the values of the *whole deviation* for each subject (Table 5).

The *whole deviation* in the blocks spontaneously curved were significantly larger than those in the blocks instructed straight for all four subjects. The results are: Spontaneously generated movements in the fronto-parallel plane were remarkably curved upward convexly, but when verbally instructed straight, the subjects could generate straighter trajectories.

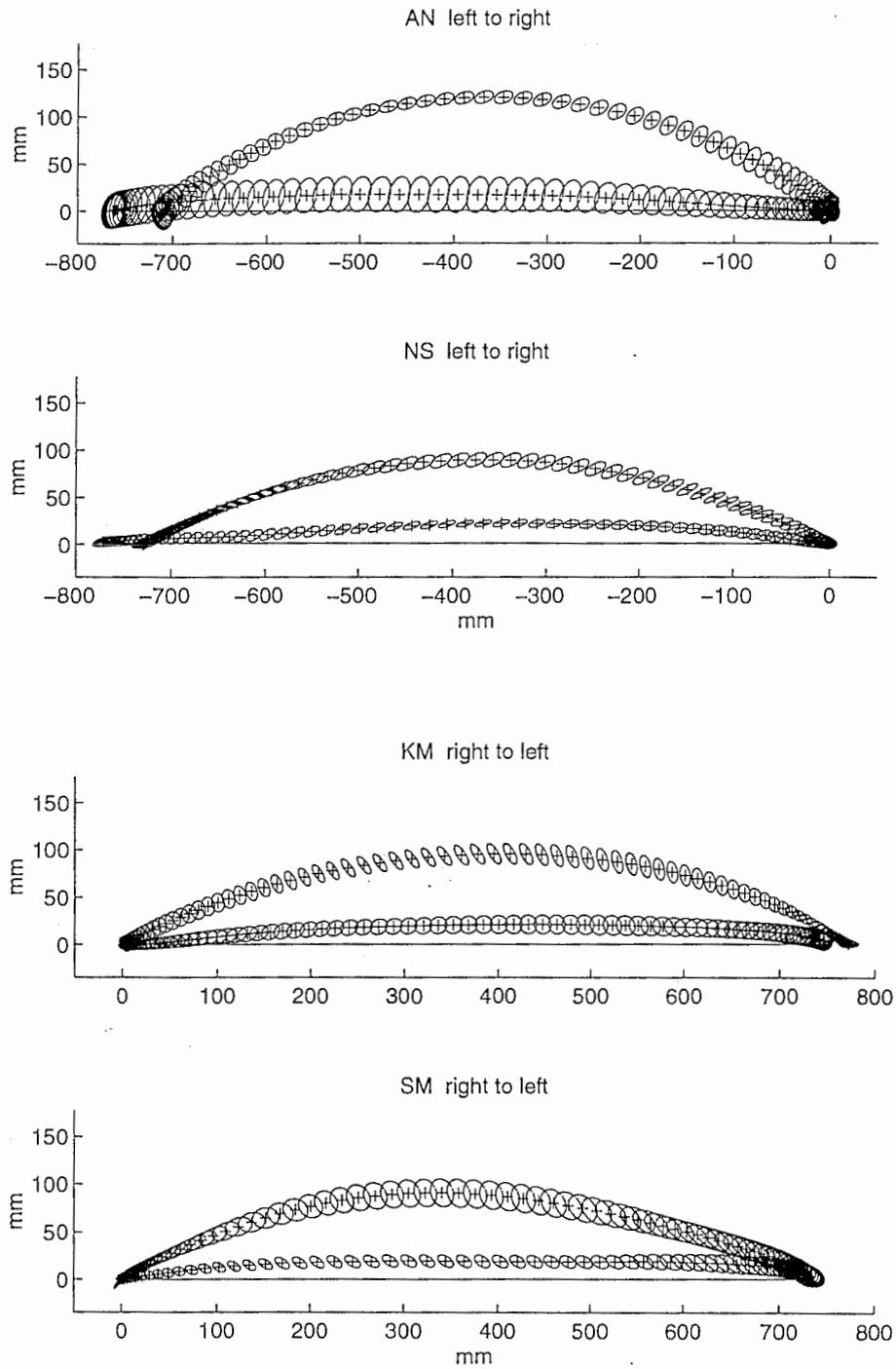


Figure 7. Averaged hand paths and standard deviation in the fronto-parallel plane for each test block and each subject in Experiment 2. The horizontal axis denotes the horizontal movement direction and the vertical axis denotes the vertical direction on the fronto-parallel plane. See text for further explanation.

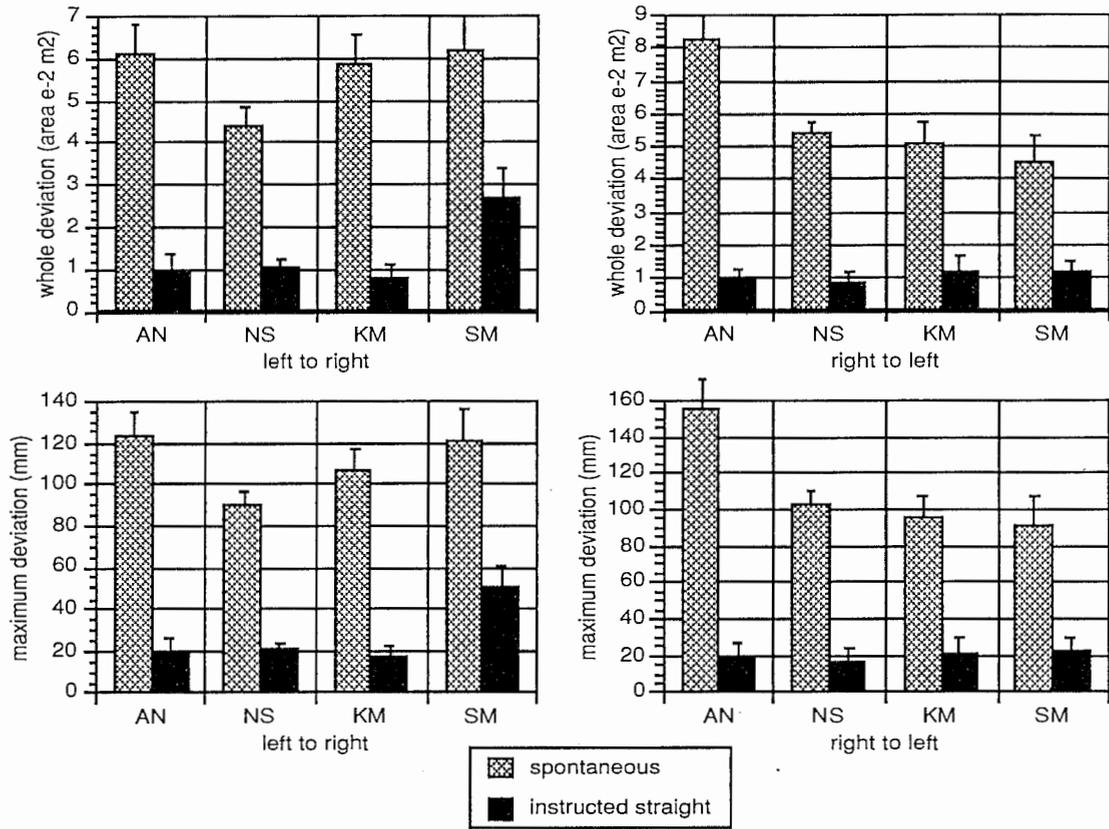


Figure 8. Mean and standard deviation of the *whole deviation* (upper panel) and the *maximum deviation* (lower panel) (see text for definition) for each test block and each subject in Experiment 2.

Table 5. *T-test for the Whole Deviation between Spontaneous and Instructed Straight Movements*

block	left-right		right-left	
	t		t	
AN	18.89	**	27.88	**
NS	23.28	**	28.58	**
KM	19.83	**	15.62	**
SM	10.62	**	11.56	**

*p<.05 **p<.01

In order to examine the possibility of perceiving spontaneously curved hand movements within the fronto-parallel plane as being straight, we compared the curvature of these spontaneous hand movements with the curvature of a cursor movement perceived as straight; the latter was obtained in the informal experiment for movement perception described in the Introduction. Figure 9 shows the results. The solid curve between the dashed curves denotes the path perceived as moving straight. The amplitude of the dashed semisinusoids correspond to the upper and lower limit of the 95% confidence interval. The other eight solid curves denote semisinusoids whose amplitude corresponds to the *maximum deviation* for spontaneously curved movements both from left to right and from right to left, for each subject.

Because the amplitude of the curvature for the hand movements was not close to but rather far away from the 95% confidence interval, we may conclude that it is improbable that spontaneously curved hand movements within the fronto-parallel plane was perceived as straight.

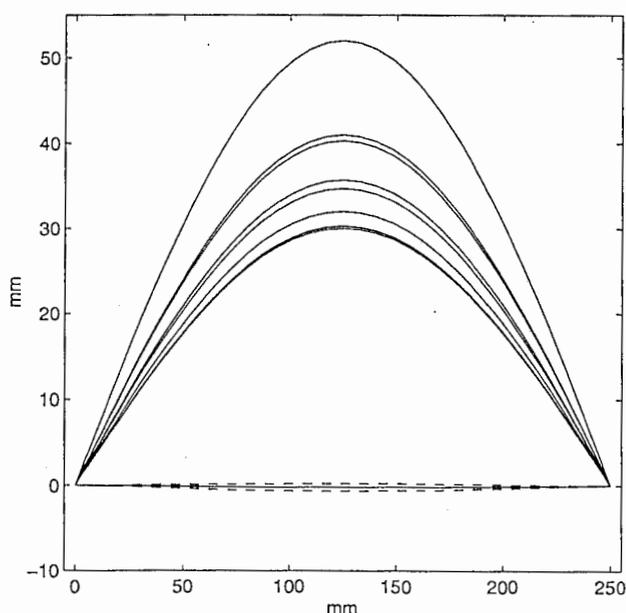


Figure 9. Comparison between the curvature of a cursor movement path perceived as straight and that of spontaneous hand movement paths within fronto-parallel plane. See text for further explanation.

Experiment 3

Method

Subjects

Four subjects participated in Experiment 3. Two of them had participated in the previous two experiments, while the other two were new.

Apparatus

The position sensing was the same as that in Experiments 1 and 2. EMG signals were recorded from six muscles. For the flexion/extension of the shoulder joint, the Anterior Deltoid and Posterior Deltoid were measured. For the double-joint muscles, the Biceps Longus (flexor) and Triceps Longus (extensor) were measured. For the elbow flexion and extension, the Brachialis and Triceps Medialis were measured. The EMG signals were recorded using a pair of silver-silver chloride surface electrodes in a bipolar configuration. Each signal was sampled at 2000 Hz with 12-bit resolution. The EMG signals were scaled for each subject so that the values at maximum co-activation in the experimental postures were contained within the range of 10.

Procedure

The instructions given to the subjects were the same as those used under conditions 1, 3 and 4 in Experiment 1. The conditions were given in the following order: 1-3-4-4-3-1. Each condition consisted of three blocks of ten trials, with short rest periods provided between every two blocks. The final blocks in the second half under instructions 3 (block

15) and 1 (block 18) were selected as the test blocks, as they were after sufficient learning. (See the lower table in Table 1.)

Data Analysis

The projection and selection of the coordinate system of the three-dimensional trajectories were done in the same way as in Experiment 1. Filtering and estimation of the movement time were done in the same way as in Experiment 1. Each trial in the test blocks was analyzed in the following way.

Calculation of averaged EMG signals.

EMG signals were digitally rectified, averaged for 0.5 ms, sampled at 200 Hz, and finally, filtered by a 25-ms moving average window. To examine the co-activation, we first aligned profiles of the averaged EMG signals in each test block at the beginning of the movements determined by the curvature criterion, and then averaged them.

Calculation of angular position and torque.

Time-normalized angular positions were calculated from time-normalized position data of hand, elbow and shoulder projected onto the horizontal plane. Derivatives of the angular position were calculated using the same technique used in Experiments 1 and 2. Time-normalized torques were calculated through the dynamics equation of a two-joint arm model using time-normalized angular variables and link parameters estimated from the link lengths for each subject (see Appendix B).

Results

The features of the hand trajectories were the same as in Experiment 1 for all four subjects, that is, the trajectories spontaneously generated

(block 18) were remarkably more curved outward convexly than those instructed straight (block 15).

Co-activation

An investigation on the profiles of the averaged EMG signals in each pair of flexion/extension muscles for each subject suggested that co-activation in instructed straight trajectories is not much higher than that in spontaneously curved trajectories. The results are shown in Figure 10. For the shoulder joint muscles, in three subjects (NS, TM, UH), the activation of the flexor (Anterior Deltoid) in instructed straight movements was not higher than that in spontaneously curved movements although the extensor (Posterior Deltoid) was more highly activated in the instructed straight movements. In the case of subject AN, the activation of both the flexor and the extensor in instructed straight movements was not higher than that in spontaneous movements. For the double joint muscles, in three subjects (AN, NS, UH), the activation of the extensor (Triceps Longus) in instructed straight movements was not higher than that in spontaneously curved movements although the flexor (Biceps Longus) was more highly activated in the instructed straight trajectories. In the case of subject TM, the co-activation of the instructed straight movements was not higher than that of the spontaneous movements in the middle of the movements while it was higher at the end of the movements. For the elbow joint muscles, in two subjects (AN, NS), the activation of the extensor (Triceps Medialis) in instructed straight movements was not so much higher than that in spontaneously curved movements although the flexor (Brachialis) was more highly activated in the instructed straight trajectories. In the case of subject UH, the activation of both the flexor and the extensor in instructed straight movements were not higher than that in spontaneous movements.

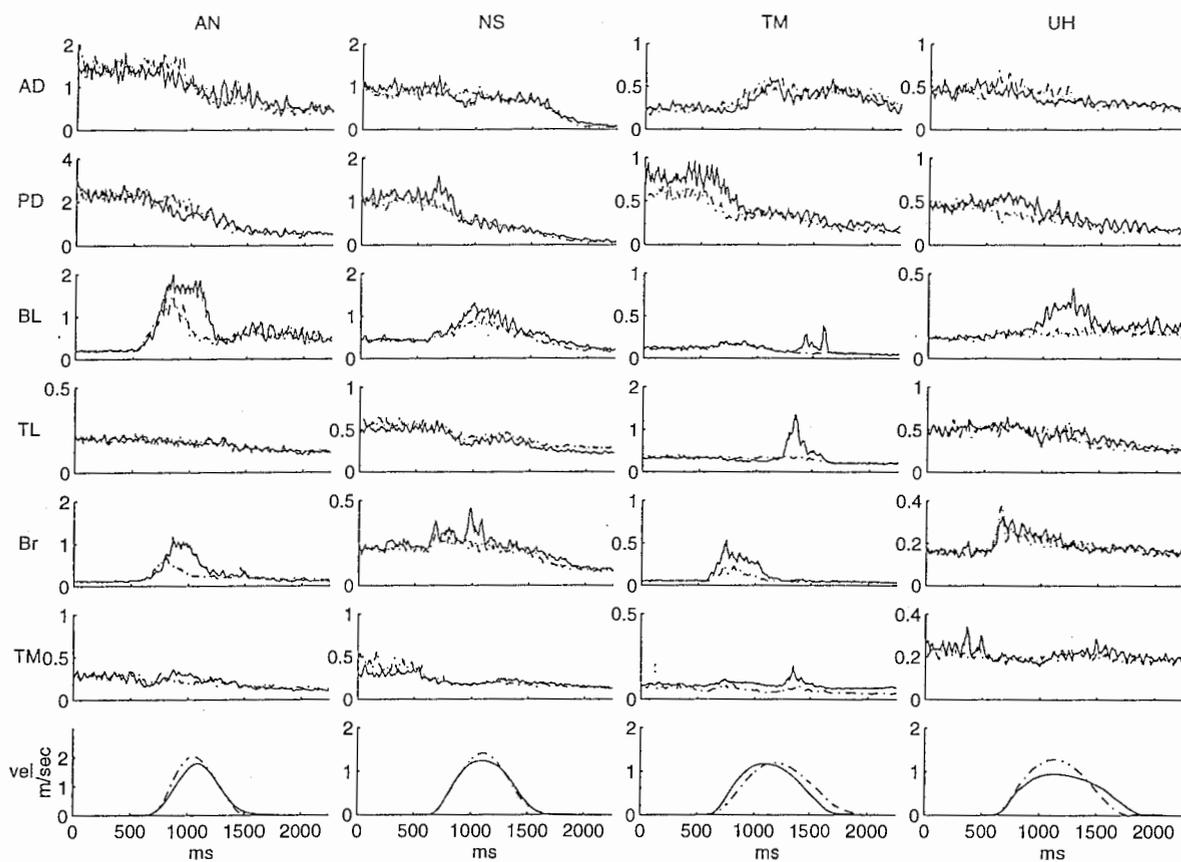


Figure 10. Time profiles of averaged EMG signals for each subject in Experiment 3. The dashdot curves denote spontaneously curved movements. The solid curves denote instructed straight movements. From top to bottom, shoulder joint flexor (Anterior Deltoid), shoulder joint extensor (Posterior Deltoid), double joint flexor (Biceps Longus), double joint extensor (Triceps Longus), elbow joint flexor (Brachialis), and elbow joint extensor (Triceps Medialis). The bottom figure denotes the averaged tangential velocity.

Profiles in Joint Angle Space and Torque Space

Figure 11 shows the averaged joint angle trajectories and their standard deviation. The cross denotes the average shoulder-elbow joint angle positions sampled at 40 Hz. The ellipses are the same as those in Figure 3 for Experiment 1. The upper, markedly curved plots for each subject denote the instructed straight trajectories. The lower, gently curved plots for each subject denote the spontaneously curved trajectories.

The trajectories spontaneously curved in Cartesian space were found to be rather straight in joint angle space whereas the instructed straight trajectories were found to be quite curved in joint angle space. The joint angle trajectories for the instructed straight movements contained joint reversal for both the shoulder and elbow joints.

The time profiles of torques were different between the spontaneous and instructed straight movements. Figure 12 shows the averaged time profiles of time-normalized torques. For all four subjects, the flexion torque for the shoulder joint increased and decreased earlier in spontaneous movements than in instructed straight movements. The peaks of the flexion torque for the shoulder joint were also earlier in spontaneous movements for three subjects (AN, TM, UH). The intervals between the peaks of the shoulder flexion torque and the elbow flexion torque were larger in instructed straight movements than in spontaneous movements for all four subjects. The peaks of the elbow flexion torque were earlier than those of the shoulder flexion torque in instructed straight movements whereas they were almost the same in spontaneous movements. The intervals between the peaks of the shoulder flexion torque and the elbow flexion torque in instructed movements were 130 msec for subject AN, 108 msec for subject NS, 155 msec for subject TM, and 143 msec for subject UH, whereas those in spontaneous movements were 25 msec for subject AN, 18 msec for subject NS, 5 msec for subject TM, and 10 msec for subject UH.

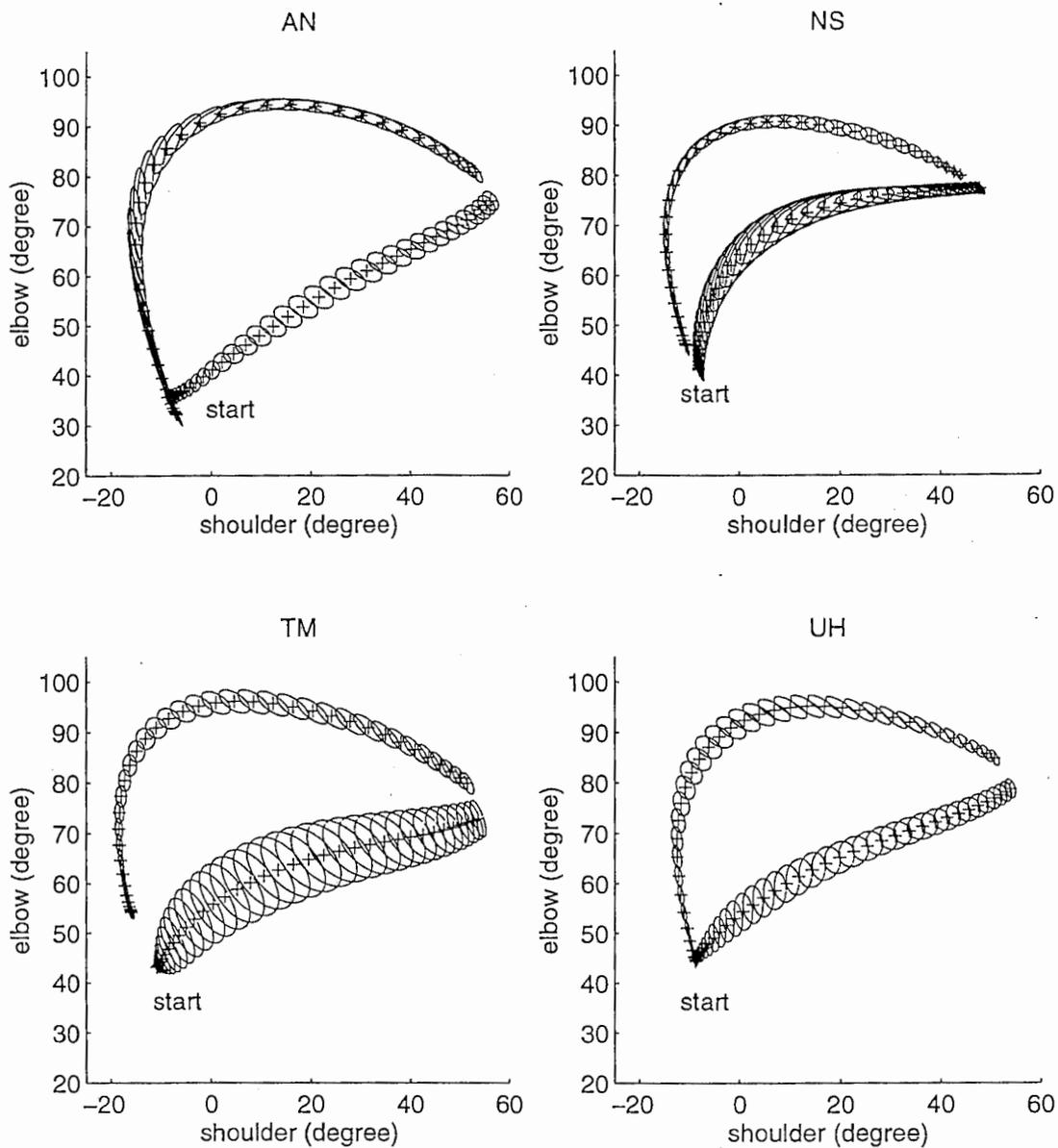


Figure 11. Averaged joint angle paths and standard deviation for each test block and each subject in Experiment 3 (in degree). The upper, markedly curved plots for each subject denote the instructed straight trajectories. The lower, gently curved plots for each subject denote the spontaneously curved trajectories. See text for further explanation.

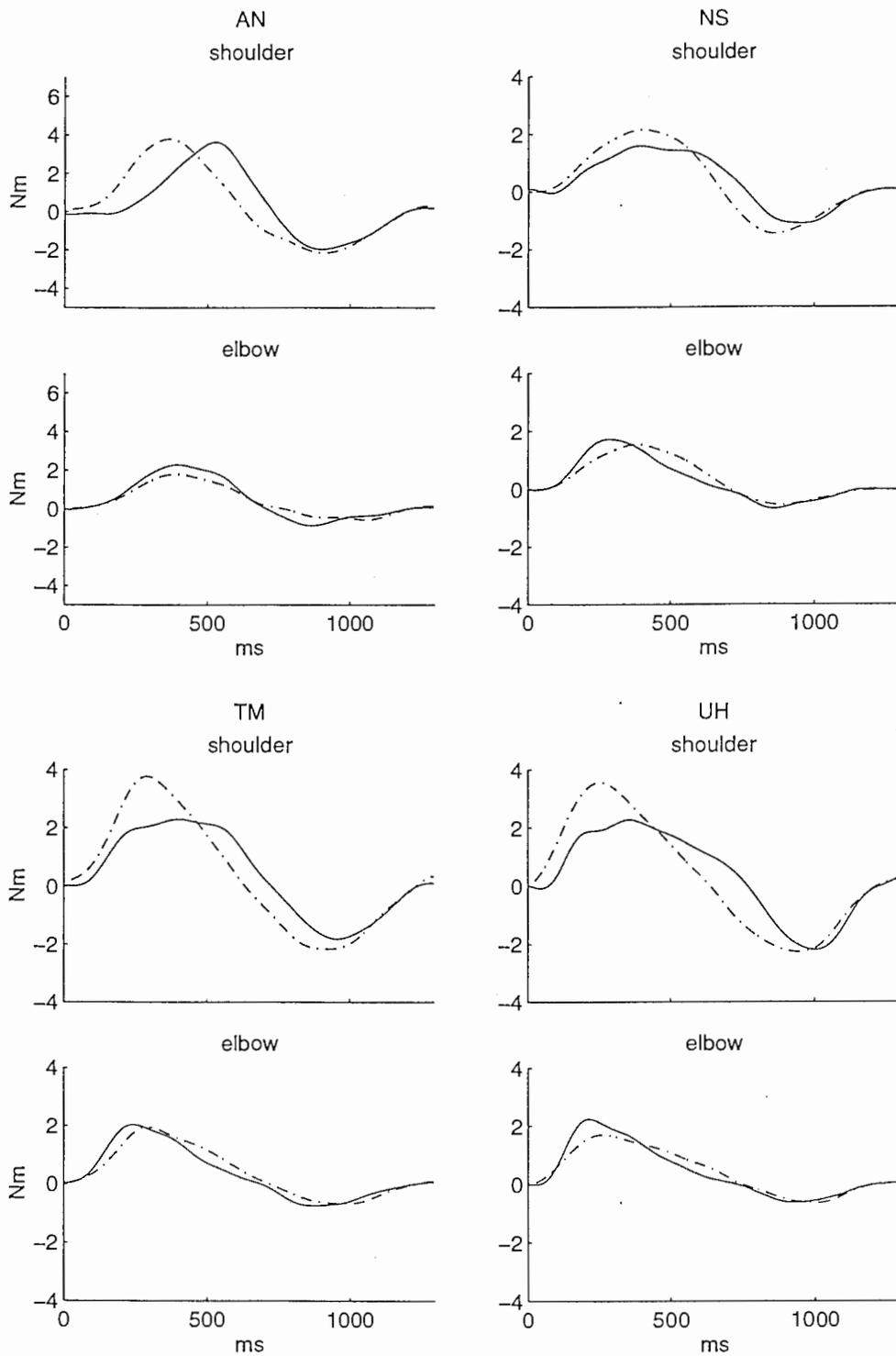


Figure 12. Averaged time profiles of torque for each subject in Experiment 3 (in Nm). The dashdot curves denote spontaneously curved trajectories. The solid curves denote instructed straight trajectories. The upper figures of each subject denote torque fed to the shoulder joint and the lower figures denote torque fed to the elbow joint.

Discussion

Curvature in Spontaneous Movements

Imperfection of control & visual perceptual distortion.

As the subjects were able to generate straighter trajectories when they were instructed to do so in both horizontal and fronto-parallel movements, the imperfection of control is not the main reason for the large curvature in spontaneous movements. The curvature in spontaneous movements in the fronto-parallel plane cannot be ascribed to visual perceptual distortion either. In horizontal movements, since the curvature was remarkably smaller in instructed straight movements than in spontaneous movements (see Figures 3 and 5), visual perceptual distortion cannot explain the major part of the curvature. Thus, both the imperfection of control and visual perceptual distortion cannot be major reasons for the curvature in spontaneous movements.

Does the imperfection of control or visual perceptual distortion then partly contribute to the large curvature in spontaneous movements? The curvature in instructed straight movements with visual guidance (with straight guidance, block 22 in Experiment 1) suggests that imperfection of control does exist in this condition and that it causes curvature in these movements. But this does not necessarily mean that the imperfection also contributes partly to the large curvature in spontaneous movements. In intrinsic planning, the CNS does not try to satisfy a hand path specified in external space so long as it can achieve targets or avoid obstacles. Therefore, if the subjects cannot reach targets or cannot avoid obstacles, control may be imperfect. Otherwise, control is successful in the sense that the goals of the movements are achieved however complicated or curved the paths between the targets may be.

Wolpert et al. (1994) suggested that the comparison of models of human trajectory formation must take into account the perceptual process by which trajectories are evaluated. If the desired trajectories are planned in extrinsic space as they assumed, we should take into account the perceptual distortion of the external world. However, if the desired trajectories are planned in intrinsic space, we may say that the perceptual distortion of the external world will not contribute to the shape of the hand paths between the targets because the controller need not pay attention to how the hand paths look so long as the hand reaches the target.

We would like to conclude that imperfection of control or visual perceptual distortion does not so much contribute to the large curvature in spontaneous movements as they do to the curvature in instructed straight movements.

Minimum-jerk virtual trajectory.

The following two facts observed in Experiment 3 contradict the possible strategy of combining the straight virtual trajectories with high stiffness for instructed straight trajectories. The first is that the co-activation level did not seem to be raised because the activation of the antagonists showed little difference even though activation of the agonists was raised. The second is that the time profiles of torques were quite different between the spontaneously generated movements and the instructed straight movements (see Figure 12). Using the same virtual trajectories as control signals in both spontaneous movements and instructed straight movements means that the descending commands that activate the muscles are changed only with the same ratio, or they are the same and the reflex gain is changed. It seems difficult to generate observed different torque profiles, especially at the beginning of the

movements, by just changing the values of stiffness using the same virtual trajectory. This suggests that the descending commands fed to the muscles did not have the same pattern but were quite different between the two movements; this contradicts the hypothesis that the CNS is always using the straight virtual trajectories calculated in the extrinsic coordinates as the control signals.

These facts, however, do not contradict the possible strategy of changing the virtual trajectory itself for instructed straight trajectories. That is, in spontaneous movements, minimum-jerk virtual trajectories are used, while in instructed straight movements, complicated virtual trajectories which can realize straight trajectories under low stiffness values are calculated. But, to begin with, as mentioned in the Introduction, control by a minimum-jerk virtual trajectory under measured, low stiffness values itself is in doubt because the realized trajectories will be overly curved and will not even come close to the target points. Because of the ease of the calculation, the minimum-jerk trajectories are used as virtual trajectories in Flash (1987)'s model. The calculation of complicated virtual trajectories is no longer a simple strategy based on the extrinsic coordinates with no knowledge of the dynamics, which was the advocated computational advantage of the virtual trajectory control hypothesis, and this calls into question the plausibility of this hypothesis.

We may go on from the above discussion that questions the plausibility of the virtual trajectory control hypothesis, and conclude that the third explanation, which is based on the virtual trajectory control hypothesis, is also implausible.

Surviving possibility.

Experiments 1 and 2 showed that the imperfection of control and visual perceptual distortion cannot explain a major part of the curvature in spontaneous movements. A series of studies (Gomi, Koike, & Kawato, 1992; Bennett, 1993; Katayama & Kawato 1993; Gomi & Kawato, 1995) gives results that contradict the minimum-jerk model combined with the virtual trajectory control hypothesis. The results of Experiment 3 also showed that it is implausible to think that the CNS controls movements using a minimum-jerk virtual trajectory by changing the values of stiffness. Therefore, the surviving possibility which can explain the fact that spontaneous movements are curved but instructed straight movements are straighter is: Planned trajectories themselves are curved.

Because there is no plausible reason to plan a curved trajectory in extrinsic space, the trajectories must be planned in one of the intrinsic spaces rather than in extrinsic space. Among the intrinsic space variables, intrinsic-kinematic planning, e.g., the joint angle space, is rejected due to the inconsistency with human data. Thus, the intrinsic-dynamic space is the likeliest candidate for the planning space of human multi-joint arm movements.

Curvature in Instructed Straight Movements

Although the subjects proved to have planned curved trajectories in spontaneous movements, they must have planned straight trajectories when they were asked to generate straight trajectories. But the subjects could not generate a perfectly straight trajectory even when straight visual guidance was given in the workspace region of the present experimental setting. Why couldn't the subjects perfectly satisfy the path constraints that existed in this case: the goal of the movements?

Spontaneous movements are nearly straight in some regions of the workspace but curved in other regions. It would be easy to generate straight trajectories in regions where the spontaneous movements are also straight because trajectories in intrinsic space that generate straight trajectories in Cartesian space will also be smooth and well experienced. On the other hand, it would be difficult to generate straight trajectories in regions where the spontaneous movements are curved because trajectories in intrinsic space that generate straight trajectories in Cartesian space will be complex and inexperienced. Thus, the imperfection of control is revealed more remarkably in the latter case than in the former case. In Experiment 1, deviation from the curved guidance was smaller than deviation from the straight guidance (see Figure 6 and Table 4). As the curved reference was the average of the spontaneously generated trajectories, the path along the curved reference must have reflected well experienced movements and must have been smooth at the motor command level. Thus, it may not have been so difficult to satisfy the path constraint in the Cartesian space. On the other hand, as the path along the straight reference was an unfamiliar movement, the subjects must have had difficulty in perfectly following the reference. The curvature observed in the instructed straight movements was outward convex, which is a feature similar to spontaneous movements. This may be because the subjects were influenced by and pulled into the well experienced patterns of motor commands. The sequence of the motor command satisfying the straight path constraints may be quite roundabout in the motor command space. It seems probable that the subjects tend to take shortcuts in the motor command space, that is, well experienced motor command sequences, resulting in a deviation in a direction similar to that of the spontaneous movements. Such effects of experience will also be revealed when the subjects give up and fail to make an extra effort to correct their

performance because of difficulty or laziness, although the subjects know that the hand paths are not what they should be.

Contribution of the visual perceptual distortion to the instructed straight movements and movements with straight visual guidance may depend on whether the distortion of the space where the path constraints are represented is also distorted or not. In verbally instructed straight movements, the subjects must specify the path constraints that they think they should satisfy. If the space where the path constraints are represented is also distorted in the same way as the visual space is distorted, such distortion contributes to the curvature because in verbally instructed straight movements, the CNS calculates the path constraints expected to appear straight in that distorted space. If these path constraints are projected onto the real Cartesian space, they should be curved outward convexly because the trajectories that look straight are convex in Cartesian space. In the movements with straight visual guidance, as the straight visual guidance looks concave to the subject's body, the path constraints represented in the distorted space also appear curved inward. The CNS generates a motor command that satisfies the path constraints appearing curved inward in the distorted space but straight in Cartesian space. Then, the realized trajectories in Cartesian space should be straight, that is, distortion does not contribute to the curvature in the movements with visual guidance. However, if the space where the path constraints are represented is exactly the same as the Cartesian space, the curvature in verbally instructed straight movements should not be so large because straight path constraints specified by the CNS will also look straight in Cartesian space. The experimental result of a larger curvature in the first verbally instructed straight movements (instructed straight 1st) than in movements with straight visual guidance (with straight guidance) suggests that the space where the path constraints

are represented seems to also be distorted in almost the same way as the visual space is distorted (see Figure 5 and Table 2).

The curvature observed in the instructed straight movements in Experiment 1 may be explained by the above reasons, that is, imperfection of control, laziness and distortion of the space. The curvature observed in the movements verbally instructed straight (instructed straight 1st) may have involved all of the reasons. The curvature observed both in the movements instructed straight with visual guidance (with straight guidance) and without after learning (instructed straight 2nd) may well have involved the imperfection of control and/or laziness. The improvement for two of the subjects and the decline for the other two in instructed straight movements after learning (instructed straight 2nd) compared to movements with straight guidance suggests the extent of this laziness, or, the extent of efforts made to satisfy the path constraints against the smoothness requirement in intrinsic space, rather than perceptual distortion, because the latter two should have known the correct path to follow.

Conclusion

We examined the planning space for multi-joint arm movements through behavioral experiments. The experimental results revealed that planned trajectories themselves are curved. We concluded that these curved trajectories are planned in the intrinsic body space while taking into account the dynamics of the musculoskeletal system.

Acknowledgment

We would like to thank Dr. Daniel Wolpert very much for sending us his unpublished manuscripts; they revived our interest in this problem. We thank Dr. Toshio Inui for giving us the chance to do this research and for his helpful suggestions. We thank Dr. Yoh'ichi Tohkura of ATR Human Information Processing Res. Labs. for his continuing encouragement. We also thank the members of ATR Human Information Res. Labs. for their comments and encouragement. We are grateful to Dr. Elliot Saltzman for his editing of the first draft of this paper.

Preparation of this manuscript was supported by a Human Frontier Science Project Grant to Mitsuo Kawato and by a Fellowship grant from the Japan Society for the Promotion of Science for Japanese Junior Scientists to Rieko Osu.

Appendix A

Normalization and Alignment

We adopted the method of normalization and alignment proposed by Atkeson & Hollerbach (1985). The first trial of each test block was used as a reference trajectory. The trajectories in each test block were normalized by peak tangential velocities and the length of the movement paths as follows. The time and distance scaling factors c and a were defined as:

$$c = \frac{V_{ref}}{V_{max}}, a = \frac{D_{ref}}{D}$$

where V_{max} and D are the peak tangential velocity and the length of the movement path of each trajectory, respectively. V_{ref} and D_{ref} are the peak tangential velocity and the length of the movement path of the reference trajectory, respectively. The normalized tangential velocity profile $V''(t)$ of an experimental tangential velocity profile $V(t)$ is:

$$V''(t) = cV\left(\frac{c}{a}t\right).$$

Then, the trajectories were aligned so that the intersection of an experimental tangential velocity profile with a reference tangential velocity profile would be minimum.

The averaged position and the standard deviation at each time step were calculated for this normalized profile by linear interpolation.

Appendix B

Calculation of Torque

The following dynamics equation of a two-joint arm model was used for torque calculation instead of the real musculoskeletal system.

$$\begin{aligned}\tau_1 &= (I_1 + I_2 + 2M_2L_2S_2 \cos\theta_2 + M_2(l)^2)\ddot{\theta}_1 \\ &\quad + (I_2 + M_2L_1S_2 \cos\theta_2)\ddot{\theta}_2 \\ &\quad - M_2L_1S_2(2\dot{\theta}_1 + \dot{\theta}_2)\dot{\theta}_2 \sin\theta_2 + b_1\dot{\theta}_1 \\ \tau_2 &= (I_2 + M_2L_2S_2 \cos\theta_2)\ddot{\theta}_1 + I_2\ddot{\theta}_2 \\ &\quad + M_2L_1S_2(\dot{\theta}_1)^2 \sin\theta_2 + b_2\dot{\theta}_2.\end{aligned}$$

Here, M_i , L_i , S_i , and I_i represent the mass, the length, the distance from the center of mass to joint, and the rotary inertia of the link i around the joint, respectively. The values of M_i , S_i , and I_i are estimated for each subject from measured values of L_i assuming the links are rigid. b_i represents the coefficient of viscosity and is assumed to be $0.4 \text{ kg}\cdot\text{m}^2/\text{s}$. τ_i represents the actuated torque of the joint i . The joint angle θ_i is defined as indicated in Figure B1. The links 1 and 2 correspond to the upper arm and the forearm, and the joints 1 and 2 correspond to the shoulder and the elbow.

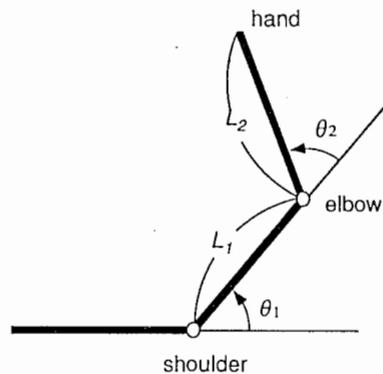


Figure B1. A two-joint arm model that moves within a horizontal plane. See text for further explanation.

References

- Abend, W., Bizzi, E., & Morasso, P. (1982). Human arm trajectory formation. *Brain*, 105, 331-348.
- Atkeson, C. G., & Hollerbach, J. M. (1985). Kinematic features of unrestrained vertical arm movements. *The Journal of Neuroscience*, 5, 2318-2330.
- Bennett, D. J. (1993). Torques generated at the human elbow joint in response to constant position errors imposed during voluntary movements. *Experimental Brain Research*, 95, 488-498.
- Bernstein, N. (1967). *The coordination and regulation of movements*. Oxford: Pergamon Press.
- Bizzi, E., Accornero, N., Chapple, W., & Hogan, N. (1984). Posture control and trajectory formation during arm movement. *Journal of Neuroscience*, 4, 2738-2744.
- Dornay, M., Uno, Y., Kawato, M., & Suzuki, R. (1995). Minimum muscle tension change trajectories predicted using a 17-muscle model of the monkey's arm. *Journal of Motor Behavior*, in press.
- Feldman, A. G. (1966a). Functional tuning of nervous system with control of movement or maintenance of a steady posture. 2. Controllable parameters of the muscles. *Biophysics*, 11, 565-578.
- Feldman, A. G. (1966b). Functional tuning of nervous system with control of movement or maintenance of a steady posture. 3. Mechanographic analysis of the execution by man of the simplest motor task. *Biophysics*, 11, 766-775.
- Feldman, A. G. (1986). Once more on the equilibrium-point hypothesis (lambda model) for motor control. *Journal of Motor Behavior*, 18, 17-54.

- Flash, T. (1987). The control of hand equilibrium trajectories in multi-joint arm movements. *Biological Cybernetics*, 57, 257-274.
- Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience*, 5, 1688-1703.
- Flowers, K. (1975). Ballistic and corrective movements on an aiming task. *Neurology*, 25, 413-421.
- Foley, J. M. (1980). Binocular distance perception. *Psychological Review*, 87:5, 411-434.
- Gomi, H., Koike, Y., & Kawato, M. (1992). Human hand stiffness during discrete point-to-point multi-joint movement. In *IEEE EMBS 94*, (pp. 1628-1629).
- Gomi, H., & Kawato, M. (1995). Mechanical impedance of human arm during unconstrained multi-joint movement in horizontal plane. *Technical report of IEICE*, in press (in Japanese).
- Haggard, P. N., & Richardson, J. (1993). Spatial patterns in the control of human arm movement. Manuscript in preparation.
- Hogan, N. (1984). An organizing principle for a class of voluntary movements. *Journal of Neuroscience*, 4, 2745-2754.
- Hogan, N. (1985). The mechanics of multi-joint posture and movement control. *Biological Cybernetics*, 52, 315-331.
- Hollerbach, J. M. (1990). Planning of arm movements. In D. N. Osherson, S. M. Kosslyn, & J. M. Hollerbach (Eds.), *Visual Cognition and Action* (pp. 183-211). Cambridge, Massachusetts: MIT press.
- Indow, T., & Watanabe, T. (1988). Alleys on an extensive apparent frontoparallel plane: a second experiment. *Perception*, 17, 647-666.

- Jordan, M. I., Flash, T., & Arnon, Y. (1993). A model of the learning of arm trajectories from spatial targets. *Journal of Cognitive Neuroscience*, In press.
- Katayama, M., & Kawato, M. (1993). Virtual trajectory and stiffness ellipse during multi-joint arm movement predicted by neural inverse models. *Biological Cybernetics*, 69, 353-362.
- Kawato, M. (1992). Optimization and learning in neural networks for formation and control of coordinated movement. In D. Meyer & S. Kornblum (Eds.), *Attention and Performance, XIV* (pp. 821-849). Cambridge, Massachusetts: MIT press.
- Kawato, M. (1995). Trajectory formation in arm movements: minimization principles and procedures. In N. Zelaznik (Eds.), *Advances in Motor Learning and Control* (In press).
- Kelso, J. A., Southard, D. L., & Goodman, D. (1979). On the nature of human interlimb coordination. *Science*, 203, 1029-1031.
- Luneburg, R. K. (1947). *Mathematical analysis of binocular vision*. Princeton University Press.
- McIntyre, J., & Bizzi, E. (1993). Servo Hypotheses for the Biological Control of Movement. *Journal of Motor Behavior*, 25, 193-202.
- Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research*, 42, 223-227.
- Mussa-Ivaldi, F. A., Hogan, N., & Bizzi, E. (1985). Neural, mechanical, and geometric factors subserving arm posture in humans. *Journal of Neuroscience*, 10, 2732-2743.
- Nelson, W. L. (1983). Physical principles for economies of skilled movements. *Biological Cybernetics*, 46, 135-147.
- Pollick, F. E., & Ishimura, G. (1995). The three-dimensional curvature of straight-ahead movements. Manuscript in preparation.

- Saltzman, E. L., & Kelso, J. A. S. (1987). Skilled actions: A task-dynamic approach. *Psychological Review*, 94, 84-106.
- Uno, Y., Kawato, M., & Suzuki, R. (1989). Formation and control of optimal trajectory in human multi-joint arm movement - minimum torque-change model. *Biological Cybernetics*, 61, 89-101.
- Uno, Y., Suzuki, R., & Kawato, M. (1989). Minimum muscle-tension-change model which reproduces human arm movement. *Proceedings of the 4th Symposium on Biological and Physiological Engineering*, 299-302 (in Japanese).
- Wann, J., Nimmo-Smith, I., & Wing, A. M. (1988). Relation between velocity and curvature in movement: Equivalence and divergence between a power law and a minimum-jerk model. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 622-637.
- Winters, J. M. (1990). Hill-based muscle models: a systems engineering perspective. In J. M. Winters & S. L.-Y. Woo (Eds.), *Multiple Muscle Systems* (pp. 69-93). New York: Springer-Verlag.
- Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1994). Perceptual distortion contributes to the curvature of human reaching movements. *Experimental Brain Research*, 98, 153-156.