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CONTROL AND COORDINATION OF VOLUNTARY ARM MOVEMENTS

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ABSTRACT

Recent findings related to the control strategies underlying voluntary arm trajectory formation in monkeys will be presented. The respective roles of central preprogramming of movements and feedback modulation from peripheral sensory organs will be discussed. A computer simulation based on mathematical modelling and dynamic optimization of the motion will be presented which predicts observed behaviour within experimental error. The same analysis also predicts observed behaviour of monkeys and humans under widely varying task conditions. Applications to the control of prostheses and manipulators will be discussed.

INTRODUCTION

The work reported in this paper is part of an ongoing study whose goal is to elucidate the control strategies adopted by the central nervous sytem (C.N.S.) when executing simple visually evoked movements. One issue of some interest is the extent to which movement is controlled by feedback modulation from peripheral sensors and the extent to which movement commands are precomputed. This is of considerable importance if the consequences of sensory and motor impairment due to amputation, spinal cord injury or neurological disease are to be understood. The basic experimental approach used in this study is to train monkeys in simple visuo-motor tasks, then deprive them of sensory information by deafferentation (bilateral section of dorsal roots from C1 to T3 and putting an opaque cover over the arm, then compare their motor behaviour before and after sensory deprivation. This paper presents the results of some recent experimental and analytical work on single-degree-of-freedom pointing tasks.

EXPERIMENTAL OBSERVATIONS

The experimental procedures and results have been described in detail in Bizzi et.al. 1982 and will only be reviewed briefly here. Experiments were performed on intact and deafferented monkeys making voluntary, pointing movements of the forearm to a visually presented target. The forearm was strapped to a splint which constrained its motion to a single degree-of-freedom rotation about a pivot coinciding with the elbow axis. A torque motor and appropriate instrumentation coupled to the forearm splint were used to apply experimental perturbations to the forearm motion. A brief perturbation applied while the animal was maintaining a fixed position resulted in a brief displacement of the limb followed by a return to the previously maintained position. Observation of this behavior in the deafferented animal demonstrated that the limb was in a stable equilibrium position in the absence of afferent feedback.

Striking and apparently paradoxical results were obtained when the forearm was displaced by the torque motor to a new position at which a target light was presented. (See Fig. 1) Shortly after the onset of agonist myoelectric activity, indicating the onset of the animal's voluntary response to the target light, the action of the torque motor ceased. Following cessation of the torque motor action the forearm started from rest at the target position and moved toward the initial position. This resulted in the surprising observation of an extensor motion taking place in the presence of predominant flexor muscle activity (Fig. 1a). After a substantial motion (up to twenty degrees) the forearm reversed direction and completed the intended movement to the target position. This behavior was observed repeatedly in intact and deafferented animals.

If the action of the torque motor held the limb in the target position for a sufficiently long period following the onset of activity in the agonist muscles, the behaviour was not observed. Instead the forearm remained in the target position when the torque motor action ceased (Fig. 1b).

THE IMPORTANCE OF MUSCLE MECHANICS

These observations add to the growing body of knowledge indicating that while afferent sensory information is accessible to the C.N.S. it is not essential for the control of movement. (Taub et.al. 1968, 1975; Bizzi et.al. 1976, 1978, 1982) Instead the mechanical and kinematic properties of the musculo-skeletal system can accomplish many of the functions previously attributed to feedback control. The apparently paradoxical results shown in Fig. 1 are readily understood if the known mechanical behaviour of muscle is taken into account. The force output from a muscle is a function not only of its neural input but also of its length and rate of change of length. (Rack et.al. 1969) Thus neural input simultaneously determines contratile force, stiffness and viscosity of a muscle. When muscles are arranged in antagonist groups about a joint, the torques due to opposing muscles subtract,

whereas the impedances add. Thus the resultant torque about a joint and the net impedance (stiffness, viscosity) may be controlled independently by appropriate simultaneous activation of antagonist muscles. The simplest mechanical description of the forearm is as a rigid link rotating about a simple pivot at the elbow. The corresponding dynamic equation is*:

$$I\ddot{\theta} = T(\underline{\alpha},\theta,\dot{\theta}) \qquad (1)$$

At equilibrium:

$$T(\underline{\alpha},\theta_o)\Big|_{\substack{\dot{\theta}=0\\ \ddot{\theta}=0}} = 0 \qquad (2)$$

The observation that the equilibrium position of the limb is maintained by the alpha motoneuron activities in the absence of feedback means that this equation may be solved explicitly to express the equilibrium position of the limb as a function of the vector of alpha motoneuron activities.

$$\theta_o = \theta_o(\underline{\alpha}) \qquad (3)$$

As a result the vector of alpha motoneuron activities may <u>always</u> be interpreted as specifying an equivalent or <u>reference equilibrium position</u> for the limb. The reference position defined by the vector of alpha motoneuron activities may differ from the actual position of the forearm (e.g. if the limb is in motion) and may lie outside of the range of reachable positions of the limb. The concept of a reference position is merely a representation of one of the mechanical consequences of a given set of input alpha motoneuron activities. It may be though of as that position towards which the limb is heading at any point in time.

When the alpha motoneuron activities vary with time, a time history of reference positions is generated which is termed the reference trajectory. A reference trajectory which undergoes a gradual (350-500ms) transition from the initial equilibrium position to the final equilibrium position can account for the observed behavior of Fig. 1. The forearm is released from rest at the target position at a time when the reference position is between initial and final positions and consequently the forearm accelerates towards it, e.g., towards extension. After a time the reference trajectory reaches the final position and remains there, whereupon the forearm also heads toward and achieves the final equilibrium position.

A MINIMUM-JERK MODEL OF POINT-TO-POINT MOTION

These qualitative predictions may be made quantitative using a mathematical model of the animal's behaviour. In reality alpha motoneuron acitivities may specify more than just a reference position for the limb. For example, the net mechanical impedance about the joint may be controlled by the co-activation of antagonist muscles (Hogan, 1980, 1982). However, for present purposes this will be neglected, and in the interest of simplicity it will be assumed that the position and velocity dependencies are uncoupled and linear. These assumptions are made explicit as follows:

$$T(\underline{\alpha},\theta,\theta) = T(\underline{\alpha}) - K\theta - B\dot{\theta} \qquad (4)$$

Rewriting in terms of the reference position we obtain a simple second order system as the model of the forearm dynamics.

At equilibrium:

$$T(\underline{\alpha}) = K\theta_o \qquad (5)$$

$$\theta_o(\underline{\alpha}) = T(\underline{\alpha})/K \qquad (6)$$

From equation 1:

$$I\ddot{\theta} + B\dot{\theta} + K\theta = K\theta_o(\underline{\alpha}) \qquad (7)$$

Equation 7 models how the forearm angle responds to neural inputs. To model the generation of neural inputs dynamic optimization techniques may be used. In the animal experiments the forearm is to make a smooth point-to-point motion. Consequently the objective function to be optimized may be stated as:

> "Generate the smoothest motion which will bring the limb from equilibrium at the starting position to equilibrium at the target position in a given time"

Maximizing the smoothness of a motion implies minimizing the jerk. Jerk is the third derivative of position and is the rate of change of accleration. Mathematically, the objective function to be minimized is:

$$C = \int_o^d \gamma^2/2\ dt \qquad (8)$$

As discussed later additional terms could be included in the cost function. However, for simplicity, only the jerk will be considered. For convenience the cost function will minimize half of the square of the jerk whereas any other even function of jerk could be used.

To permit full consideration of the constraints imposed by the dynamics of the system (equation 7) or physical limitations such as the maximum torque the muscles may exert, or the maximum speed of the forearm, etc., the method of Pontryagin,<u>et.al</u>.(1962) must be used. However, the experimental observations are of voluntary movements made at the animal's preferred speed. It is clear that the animal is not operating anywhere near the limits of neuromuscular performance. Because the objective function depends only on kinematic variables the problem may be treated as an unconstrained minimization. This will result in an "ideal" movement <u>independent of the physical system generating the motion</u>. If the "ideal" movement lies within the performance limits of the physical system then the

*See Nomenclature for explanation of symbols

motion which minimizes the objective function does not depend on the assumed form of the model of neuromuscular system, be it linear or non-linear.

Solution of an unconstrained minimization problem may be obtained using classical variational calculus. If the function $\theta(t)$ is sufficiently differentiable in the interval $0 \leq t \leq d$ then the unconstrained functional

$$C\{\theta(t)\} = \int_0^d F\{t,\theta,\dot{\theta}, \ldots \overset{(n)}{\theta}\} \quad (9)$$

assumes an extremum when $\theta(t)$ is given by the Euler-Poisson equation:

$$\frac{\partial F}{\partial \theta} - \frac{d}{dt}\frac{\partial F}{\partial \dot{\theta}} + \ldots + (-1)^n \frac{d^n}{dt^n}\frac{\partial F}{\partial \overset{(n)}{\theta}} = 0 \quad (10)$$

In this problem:

$$F\{t,\theta,\dot{\theta}, \ldots \overset{(n)}{\theta}\} = \gamma^2/2 \quad (11)$$

Applying equation 10:

$$-\frac{d^3}{dt^3}\frac{\partial}{\partial \gamma}\gamma^2/2 = 0 \quad (12)$$

$$\frac{d^6\theta}{dt^6} = 0 \quad (13)$$

The resulting position trajectory is given by a fifth order polynomial.

$$\theta(t) - C_o + C_1 t + C_2 t^2 + C_3 t^3 + C_4 t^4 + C_5 t^5 \quad (14)$$

From this one can see that the objective function determines the form of the solution. However, the actual motion profile depend critically upon the boundary conditions. For this problem the system starts and finishes at equilbrium so the boundary conditions are given as follows:

$\theta(0)=0$ (starting position)	$\theta(d)=a$ (target position)
$\dot{\theta}(0)=0$	$\dot{\theta}(d)=0$
$\ddot{\theta}(0)=0$	$\ddot{\theta}(d)=0$

Both the movement amplitude and the movement duration may be rescaled to unity without loss of generality. Solving for the undetermined coefficients we obtain the following equation for the motion:

$$\theta(t) = 10\,t^3 - 15\,t^4 + 6\,t^5;\ 0 \leq t \leq 1 \quad (15)$$

NUMERICAL RESULTS

The following characteristics of the motion may be derived:

Maximum velocity = 1.88 a/d

Maximum acceleration = 5.77 a/d^2

Maximum deceleration = -5.77 a/d^2

Observation of monkeys performing undisturbed pointing movements through a 60° arc show a movement duration of 692 ± 676 milliseconds*. Using 550 milliseconds as a representative movement duration yields for a 60° amplitude motion a predicted peak acceleration of 1150 degrees per second squared. Measured values of peak acceleration were 1130 ± 320 degrees per second squared. The minimum-jerk motion profile yields good qualitative and quantitative agreement with observed motion profiles for undisturbed movements.

In contrast to the actual motion profile, the reference trajectory, which is a summary of the control inputs required to generate the torque which produces the movement, depends heavily on the description of the physical torque-generating system. To obtain numerical results, values for the system parameters are needed. Choosing justifiable parameter values is usually the most difficult and least defensible step in any modelling exercise. The model of equation (7) has been kept as simple as possible and as a result only three parameters are needed: the inertia, stiffness and damping coefficients for the forearm. From measurements performed on intact monkeys the system parameters are as follows:

$I = 0.014$ kg - m^2

$K = 1.48$ N-m/rad

$B = 0.173$ N-m-s/rad

Using the above parameter values in equation (7) a digital simulation of the forearm was performed. The reference trajectory required to generate the motion profile of equation (14) is shown in Fig. 2 along with the actual trajectory. Note that because of the springlike behavior of the muscles the reference position must precede the actual position of the forearm in order to generate the torques necessary to produce the desired motion profile. To simulate the experiment in which the forearm was moved to the final position at the onset of voluntary motion a computation was performed using the same parameters and the same reference trajectory but with initial conditions such that the forearm was at rest in the target position at time zero. Figure 3 shows the result. As observed in the experimental animals, the limb first moved toward the starting position before reversing direction and achieving target. Thus the same alpha motoneuron activity which generated the reference trajectory and actual motion profile of Fig. 2 will also generate the motion profile of Fig. 3 when the initial conditions are changed. This can explain the extensor motion seen in the presence of flexor activity. Because the muscles

*The distribution of movement durations was heavily skewed towards shorter movement durations

are defining an equilibrium position (reference position) for the limb the initial motion of the limb is to move towards the instantaneous value of the reference position. However, as can be seen the system is slightly underdamped (ξ=0.6) and undershoots the reference trajectory. The important observation is that the extensor motion in the presence of of flexor activity implies that the reference position undergoes a gradual transition between start and final equilibrium positions. The transition occupies about half of the movement duration, or about 250 to 300 milliseconds. After that, the reference positions stays close to the final equilibrium position.

EXPERIMENTAL TEST OF REFERENCE TRAJECTORY

Experiments were performed to investigate the time course of the reference trajectory. Before the onset of visually triggered movement the forearm was held by the torque motor in its initial position and released at various times following the onset of evoked agonist myoelectric activity. The acceleration of the limb just at the moment of release was measured. As the velocity of the limb is zero at this time, viscous torques are zero and the acceleration is proportional to the elastic torque generated by the difference between the reference position and the actual position.

Figure 4 shows a plot of the results of this experiment performed on an intact animal superimposed upon a plot of the simulated reference trajectory. The acceleration data have been plotted on vertical axis which has been scaled to produce a reasonable fit to the reference trajectory in the region where it is close to the final position. However, their time-course has been unaffected. These results provide a measure of how well the predicted time-course of the reference trajectory matches the animal's behavior. As can be seen the fit is adequate, although there is considerable scatter in the data.

DISCUSSION

These experimental and analytical results provide evidence that for the gross motion studied voluntary movements are preplanned and may be executed without peripheral feedback modulation of the descending commands. The behavior of the deafferented anaimal showed all of the major qualitative features of the intact anaimal's behavior. The major effect of deafferentation was a reduction in the values of the overall apparent mechanical stiffness and viscosity about the joint (Bizzi et.al. 1982) This is consistent with the removal of proprioceptive feedback loops which contribute to the apparent stiffness and viscosity through negative position and velocity feedback.

Experience gained in the development and application of assistive devices such as prostheses has shown that the human operator depends heavily on direct feedback of device behavior (typically via vision) and that an unacceptably high level of concentration is required for their operation. This has traditionally been attributed to sensory impairment which accompanies a disabling trauma such as amputation. The underlying idea is that feedback is essential for successful motion control. However, experimental results such as those presented here show that this is not the case. Instead the problems with assistive device control may be attributed to inadequacies in the forward path transmitting the operator's motor intent to the machine (Hogan, 1976). An important requirement for an assistive device controller is that it have a high-fidelity forward or command pathway. The accessible biological signals should be measured as accurately as possible and, most important, should be interpreted correctly. The modelling presented in this paper is a step towards correct interpretation of muscle activity.

The observation in both the intact and deafferented animals of extensor motion during predominant flexor activity is a compelling reminder of the fact that muscle may not be viewed simply as a pure force generator. This apparently paradoxical behavior is readily explained when the known length dependence of muscle output force is considered. The concept of a "reference position" defined by the relevant muscles is a concise and effective way of including the length dependence in a model of muscle. The alpha motoneuron activity of the relevant muscles may always be interpreted as specifying a position command (the reference position) with torque generated due to the apparent elasticity as a function of the deviation of the actual position from the reference position. However, it would be equally correct to interpret the alpha motoneuron activity as specifying a "reference torque" with the position being specified by a knowledge of the compliance of the limb and the deviation between actual output torque and the reference output torque. It is meaningless to ask whether the central nervous system commands position or torque; alpha motoneuron activity may be equally well interpreted as a position command (the reference trajectory) or as a torque command. In the foregoing, the command was interpreted as a position for reasons of clarity as it permits direct comparison of the command with the actual position.

Dynamic optimization is an essential part of the mathematical analysis. It permits global aspects of the movement to be factored into the analysis through the objective function. It brings about a dramatic reduction in the dimensionality of the problem of choosing inputs for the system model. Of the infinite set of possible commands which would bring the system from start to target in the given time, only one minimizes the objective function*.

The objective function used in this analysis, that of minimzing the square of the jerk throughout the duration of the movement, was chosen as the simplest objective function which would yield the observed motion profile. The predicted motion profile has symmetrical acceleration and deceleration phases. However, it is frequently observed that the acceleration phase of a point-to-point movement is somewhat shorter than the deceleration phase. This could readily be accomodated if the objective function were modified to include a term penalizing

*Provided the problem is non-singular

the square of the deviation of the actual position from the target position. This term would cause the controller to use higher levels of jerk and acceleration in the early portion of the movement so as to bring the error between actual and target positions down to a low value and use lower accelerations and jerks in the latter portion of the movement to offset this. The result is an asymmetric motion profile. However, the observed asymmetry is typically small. Inclusion of an additional term in the objective function would compromise the value of the analysis and detract from its simplicity and it was deemed not worth the effort.

It is tempting to try to adduce physical or physiological reasons for minimizing jerk during a motion. For example, drawing on engineering experience one might speculate that this strategy has evolved through minimizing wear and tear on the musculoskeletal system. However, caution is required. The natural movements under consideration are relatively slow and gentle movements which do not stress the animal. In contrast, the fifth-order polynomial cam is used in engineering applications in which stress, material fatigue and impact loading are the primary considerations. Thus the analogy between the engineering and physiological systems should not be taken too far. Minimizing jerk may be more closely related to maintaining system controllability than reducing trauma.

The real strength of the minimum jerk objective function, or indeed any other objective function, is its use as an orgainizing principle. In this regard, minimizing the jerk of a motion is similar to Fermat's Principle in Physical Optics which dictates that to go from one point to another a light ray follows the shortest path (more correctly the path for which transit time is an extremum). In physics Fermat's Principle is not presented as a physical cause for the path of a light ray but rather as a convenient organizing description of the path of a light ray through complex media. At this stage in the development of analytical techniques for describing natural motion control, the minimum jerk movement should be regarded as a convenient way of organizing and thinking about movements.

The main features of the point-to-point motion profile obtained by minimizing jerk are the unimodal velocity profile and the continuous acceleration profile. Motion profiles similar to those of Fig. 2 can be seen in the data for a large variety of movements, ranging from saccadic eye movements (Cook and Stark, 1968) to movements of the entire arm. (Soechting 1981, Morasso, 1981). The minimum jerk formalism is also capable of predicting the major features of more complex voluntary movement such as those described by Abend et.al. (1981). Thus the minimization of jerk may be general principle of motion control

Minimum-jerk motions may have application in the control of industrial manipulators. The fifth-order polynomial is at present commonly used for straight line motions. However curved motions through a via-point are presently planned using ad-hoc techniques such as fitting of spline functions. the minimum-jerk formulation provides an alternative and rigourous way of planning general motions in a unified manner. Curved motions through via points or back-and-forth motions between points are merely special cases with interior point constraints or alternative boundary conditions.

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NOMENCLATURE

a	movement amplitudes
d	movement duration
t	time
C	objective function
$C_0 \ldots C_5$	constraints
B	angular viscosity
K	angular stiffness
I	movement of inertia
T	torque
θ	angular position
γ	angular jerk
θ_0	reference position
$\underline{\alpha}$	a vector of motoneuron activities
( ),{ }	parentheses denote functional dependence

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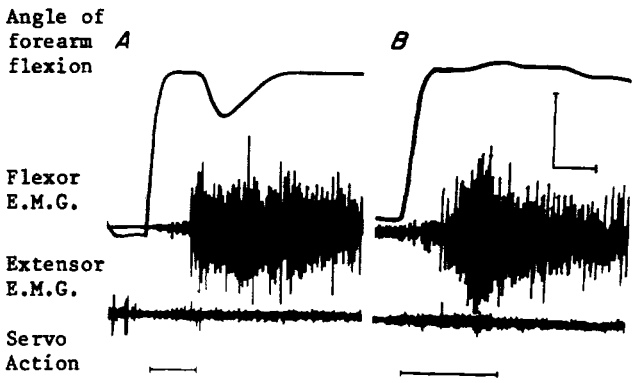

Fig. 1. A. Forearm movements of a deafferented animal in the absence of visual feedback. The forearm was displaced by servo action (indicated by horizontal bar) to a flexed position at which a target light was displayed. At the termination of the servo action shortly after onset of flexor E.M.G. note the movement toward extension and subsequent return to the flexed target position.

B. Same animal. The forearm was held in the flexed target position for an extended period following onset of flexor E.M.G. Under these conditions there was no movement of the forearm after termination of the servo action.

Calibration: Vertical bar, Joint angle, 20° horizontal bar, time, 500 ms.

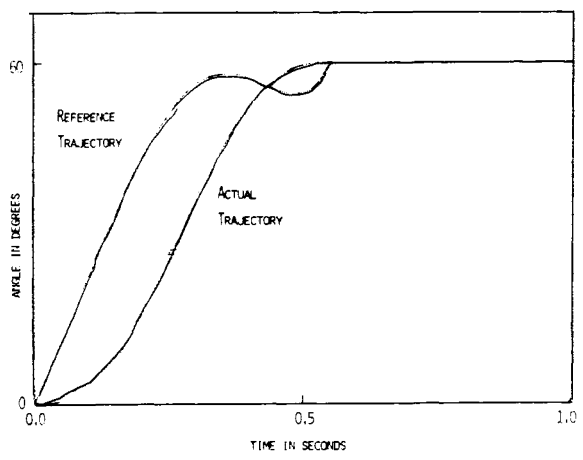

Fig. 2. Digital simulation of reference and actual trajectories for a 60° minimum-jerk movement lasting 550 ms. System parameters are for the intact animal. Note that the reference trajectory leads the actual trajectory in the early portion of the movement

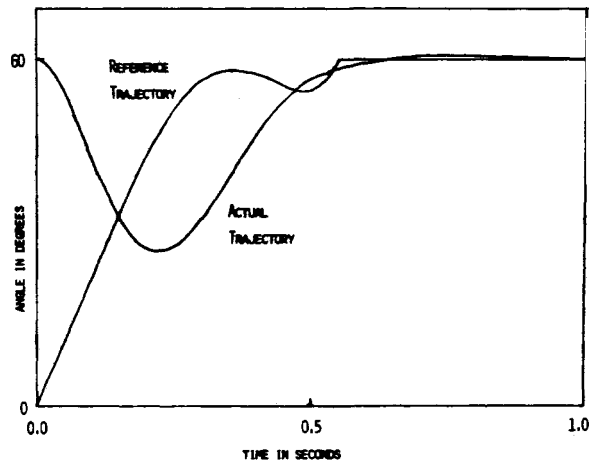

Fig. 3. Digital simulation of reference and actual trajectories for a 60° minimum-jerk movement lasting 550 ms. System parameters are for the intact animal. The actual trajectory starts from rest in the target position.

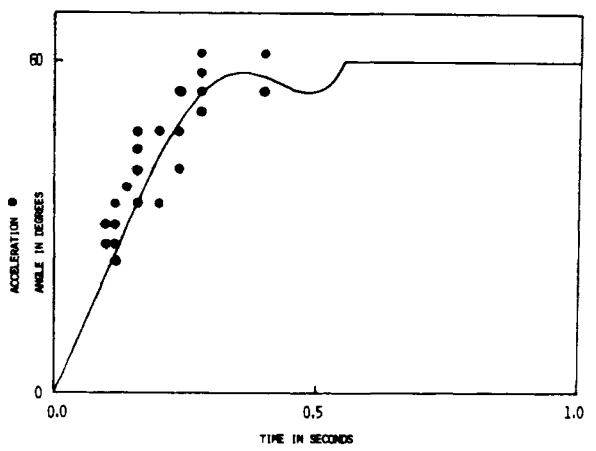

Fig. 4. Simulated reference trajectory superimposed on a plot of acceleration at release vs. time from onset of movement. The acceleration data, taken from an intact animal, has been scaled to match the reference trajectory for times greater than 250 ms. Its time-course is unchanged.