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Arm Trajectory Planning and Execution: The Problem of Coordinate Transformation

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Abstract. In this paper some of the theoretical and experimental approaches related to multijoint arm trajectory formation are discussed. The problems I have considered are (a) coordinate transformation underlying trajectory planning, (b) the approaches elaborated by computer scientists to execute movements in artificial multijoint systems, and (c) a biological perspective on the problem of computing torques with muscles.

INTRODUCTION

In this paper I will discuss some of the issues related to the way in which the central nervous system (CNS) directs the arm to a target in space. In recent years, the problem of planning a multijoint arm trajectory has been studied by both computer scientists and neuroscientists. While in the past investigators hoped to understand the scheme for multijoint control by invoking servo control mechanisms applied to individual degrees of freedom, today's neuroscientists and computer scientists favor an approach based on preplanning. Accordingly, in this chapter I will consider first the problem of transforming sensory information in order to generate a plan of action, i.e., coordinate transformation. Then I will briefly consider the approaches elaborated in the field of robotics for deriving joint torques from the planned trajectory. Finally, I will discuss a biological perspective on the problem of computing torques.

COORDINATE TRANSFORMATIONS

The first step in any preplanning of arm trajectory is to derive a representation based on the position of the target to be reached. This initial step is contingent upon transforming the retinal image of the target into head-centered and, ultimately, body-centered coordinates. The translation of retinotopic information into head-centered coordinates has been discussed by Andersen (this volume). I will only briefly mention here that this coordinate transformation occurs in the posterior parietal cortex and that this area seems, on the basis of clinical evidence, important in planning voluntary actions. In addition to the representation of the target in body-centered coordinates, the CNS must also represent the initial arm configuration in order to "plan" the arm trajectory. If the hand initial position is detected visually, then the process is identical to the one utilized for locating the target. On the other hand, if arm configuration is perceived through a combination of proprioceptors (joint, muscle, tendon receptors), then a complex and poorly understood set of transformations must occur, i.e., the position of the hand must be derived from activities specified in terms of muscle and/or joint coordinates. We do not know how the CNS accomplishes this seemingly complex readout.

Once the hand initial position and the final target are represented in the same coordinate frame, then the CNS must solve the problem of representing the "trajectory," i.e., it must plan the path and the velocity of the hand in space. There is some evidence that this representation may be formed in the posterior parietal cortex and/or medial regions of the frontal lobe. Recent studies by Georgopoulos et al. (1980), based on recording single neurons from the parietal cortex of monkeys, indicate a correlation between neural activity and the direction of movement. It is tempting to speculate that these signals may represent the physiological underpinnings of trajectory planning.

Regardless of the interpretation of Georgopoulos's data, the difficult question for motor neurophysiologists is to understand the transformation from trajectory representation into the appropriate joint motion and joint torques.

In the past, physiologists have not specifically addressed this question. The signals from "motor" areas were assumed to activate the segmental spinal cord apparatus and somewhat mysteriously generate the desired movement. Very little attention was also paid to the fact that there are dynamic interactions between moving links that have to be handled either by the "neural controller" or by the biomechanical structure. These dynamic interactions will generate torques that must be integrated with those derived from the feedforward computation. As Hollerbach (1979) has shown, these forces cannot be neglected even at fairly moderate speeds. For instance, in multijoint movements, the torque required to move one joint is dependent upon the position of the other joints. In addition, the "controller" must take into consideration the joint interactional effects which result from muscles which span more than one joint. To further complicate the computational problem of executing an arm trajectory, the CNS must deal with torques resulting from interactional forces such as the centripetal interaction torque. If there is no "compensation" for these coupling effects, motion about one joint would cause other joints to flail so that errors in joint and hand motion would occur. Whether "compensation" is achieved by specifically planned neural activities or by some other means, such as raising the stiffness of the muscles involved in trajectory formation, is not yet clear. The fact that these "compensations" for dynamic interactions are handled in robotics through the solution of equations, i.e., are explicitly "computed," does not imply that in the CNS there are specific cellular groups whose activity represents the biological equivalent of the computations described in robotics. It is entirely possible that the motor apparatus may sense the dynamic interactions as "perturbations" to be handled by increasing the stiffness of the muscles involved in executing a given trajectory.

Even though we do not know how the CNS solves this problem, I do want to stress the usefulness of robotic work in this area. The study of artificial systems has indicated the need to pay attention to Newtonian mechanics in the nontrivial case of a multijoint system. While emphasizing the role of mechanics may not be considered a stunning revelation, the fact remains that physiological thinking in the area of motor control has ignored the complexity of dynamic interactions in systems with many links.

Coordinate Transformations in Artificial Systems

In the field of robotics, two alternative approaches have been proposed to transform the planned trajectory in the appropriate joint motions and torques. (These steps are called inverse kinematics and dynamics.) One method is based upon solving the equation of motion, the other, on obtaining the required torques from a look-up table indexed by the state variables, θ, $\dot{\theta}$, $\ddot{\theta}$. The tables may be derived either by precomputation or by associative learning. In robotics, the look-up table method was favored because computing inverse dynamics for a complex multijoint system, in a reasonable time, was quite difficult. However recently, methods which allow rapid computation of torques have been found (Hollerbach 1979; Luh et al. 1980). It should also be stressed that there are drawbacks with the look-up table method. The main objections are that it requires a very large memory and that the method is sensitive to configuration, i.e., any change in the system such as an applied load requires a completely new table.

While in the context of today's computers it makes sense to consider the dichotomy of the tabular versus analytical methods, a different perspective must be taken when considering the biological motor control system. Both the analytical equation method and the look-up approach do not provide, in my view, a useful frame of reference for the biologist interested in understanding motor control. These methods fail to be biologically relevant because they do not provide any indication on how the motor controller may exploit the constraints inherent in the physics of motor control, the geometrical structure of the muscles around the joints, and the tasks required of the limb. Furthermore, they are not helpful in the identification of the modules in which the biological system must be organized and in explaining how short- and long-loop reflexes and motor maps cooperate in planning and executing of movement.

Coordinate Transformations in Biological Systems

Recent experimental work has focused on muscle mechanical properties. Feldman (1966) and others (Cooke 1979; Kelso 1977; Kelso and Holt 1980; Nichols and Houk 1976; Rack and Westbury 1969) have suggested that a muscle is mechanically analogous to a spring, whose stiffness is a function of its activation. As with a spring, a muscle's force is a function of its length. The position at which the length-dependent forces due to opposing muscles are equal is an equilibrium position of the limb. Consequently, the CNS may maintain a desired joint position by simultaneous activation of agonist and antagonist muscles. This view of posture, in its simplest formulation, implies that each joint position is coded in the CNS by a single scalar quantity, the ratio of agonist and antagonist forces (Lestienne et al. 1981).

Experimental studies of visually triggered head and arm movements in trained monkeys (Bizzi et al. 1976; Polit and Bizzi 1979) have shown that a final head and/or forearm position is indeed an equilibrium point between opposing forces. Also, these investigations showed that monkeys can execute simple single joint pointing movements of the forearm and maintain briefly (1 s) the forearm in a new equilibrium position in the complete absence of proprioceptive feedback from forearm muscles and joints (Polit and Bizzi 1979). These findings imply a functional relationship between the descending commands to the relevant muscles and the equilibrium position of the forearm. Furthermore, recent experimental evidence indicates that the transition from one arm posture to another is achieved by adjusting the relative intensity of neural signals to each of the opposing muscles so that the equilibrium point defined by their interaction moves toward either flexion or extension of the limb. According to this view, single joint arm trajectory is obtained through neural signals which specify a series of equilibrium positions for the limb.

The experimental results supporting this view, for a 60° movement of the forearm lasting 600 ms, are that the torque produced by the alpha motoneuronal activity did not reach steady state until 400 ms had elapsed after the onset of action potentials in the muscle (Bizzi et al. 1984). This was clearly seen when a target specifying a 60° forearm movement was presented and the arm was held at the initial position for various durations. It was found that the initial acceleration after release of the forearm increased *gradually* with the duration of the holding period, reaching a steady-state value no sooner than 400 ms after the onset of electromyographic (EMG) activity. Equivalently, the torque generated in response to alpha motoneuronal activity during the holding period at the initial position increased *gradually* with time, reaching a peak for 60° movements at 488 ms (average value) after the onset of EMG activity. Taken together these results show that the CNS had programmed a slow, gradual shift of the equilibrium point (Bizzi et al. 1984).

Additional support was found by experiments based upon forcing the forearm to a target position by an assisting torque pulse applied at the beginning of a 60° forearm movement. After reaching target position, the forearm returned to a point between the initial and final target positions before proceeding to the endpoint. This observation suggests that the alpha motoneuronal activity specifies a series of equivalent equilibrium positions throughout the movement. If the muscles merely generated force during the transition phase of a movement, one would not have seen the return motion of the limb. However, it is well known that the force generated by a muscle is a function of its length and that the torque generated by a group of muscles is a function of the angles of the corresponding joints. As a direct result of this position dependence, the alpha activitiese of the muscles can always be interpreted as specifying an equilibrium position, along with a stiffness about this position. Thus, in the transition from the initial to the final limb position, the alpha motoneuronal activity is defining a series of equivalent equilibrium positions ("virtual position" and its time history, the "virtual trajectory" (Hogan 1984)).

It must be stressed that the dependence of muscle force on muscle length means that alpha motoneuronal activity can be interpreted as commanding either a limb position, with the stiffness specifying a force corresponding to the difference between the actual and the commanded positions, or a force, with the stiffness specifying the position corresponding to the difference between the actual and the commanded forces. A question of long-standing interest in the neurophysiology of motor control has been whether a descending command specifies a position or a force. If the characteristics of muscle are such that force and length are uniquely related, then the two are mechanically equivalent and indistinguishable. In postulating that forearm trajectory is determined by a series of positions or forces, we have applied known length-tension relationships derived under static conditions to a dynamic situation. Although such factors as the relationship between force and velocity and the history of muscle activation may alter the length-tension relationship during movement, we feel that the static extrapolation provides insight of single joint studies (Hogan 1984).

It should be stressed that the forearm movements studied by Bizzi et al. (1984) were performed at moderate speed. It is conceivable, for very fast movements, that the shift in equilibrium point may be more abrupt (step-like) or may even specify a point beyond the intended equilibrium point (Hogan 1984), which would amount to a pulse-step command of the type known to control eye movements (Robinson 1970) and fast limb movements (Desmedt and Godaux 1978).

The idea that postural stability results from the CNS coordinating the activity levels of agonist and antagonist muscles around a joint, so that an equilibrium position is defined, has recently been extended to the multijoint case. To deal with the richer and more complex situation of the multijoint arm, a new approach to the study of posture and movement was developed. This approach entailed displacing the hand (see Fig. 1) in any different direction and each time determining the resulting restoring forces before the onset of any voluntary reaction. The stiffness in the vicinity of the hand equilibrium position was estimated by analyzing the force and displacement vectors. The stiffness field was represented as an ellipse characterized by three parameters: magnitude, shape, and orientation (direction of the major axis). This representation captures the main geometrical features of the elastic force field associated with a given hand posture.

The spring-like behavior of four subjects performing a posturing task is shown in Fig. 2 (Mussa-Ivaldi et al. 1985). The stiffness ellipses measured at given work space positions are shown along with a schematic display of

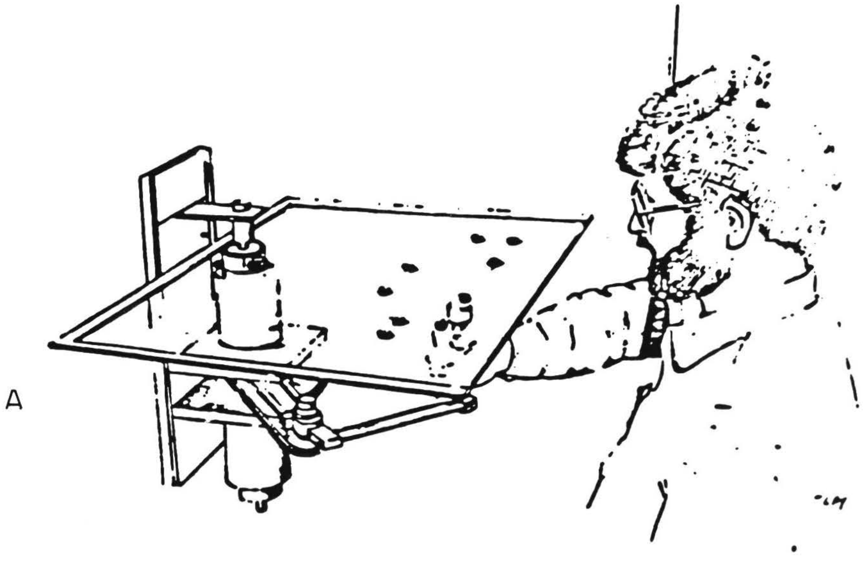

Fig. 1—From Mussa-Ivaldi et al. 1985.

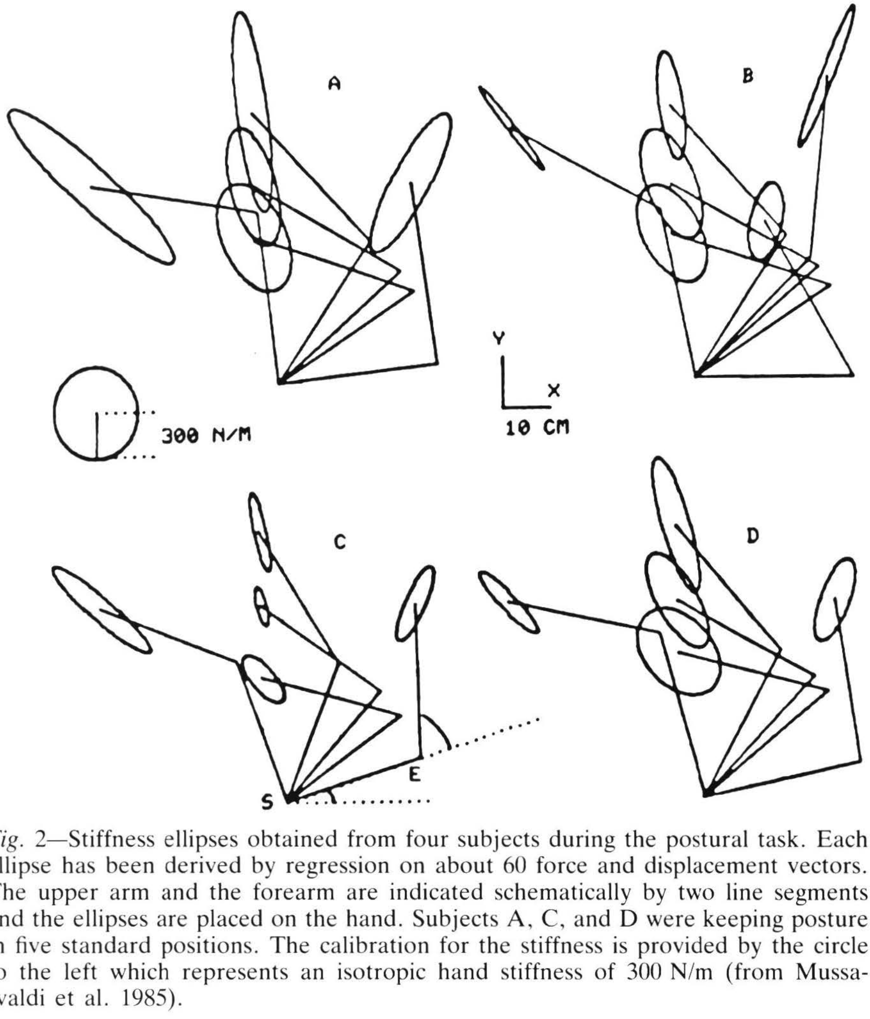

Fig. 2—Stiffness ellipses obtained from four subjects during the postural task. Each ellipse has been derived by regression on about 60 force and displacement vectors. The upper arm and the forearm are indicated schematically by two line segments and the ellipses are placed on the hand. Subjects A, C, and D were keeping posture in five standard positions. The calibration for the stiffness is provided by the circle to the left which represents an isotropic hand stiffness of 300 N/m (from Mussa-Ivaldi et al. 1985).

the corresponding arm configurations. A remarkable feature of these data is the similarity of the stiffness orientation for different subjects. At any given location the shape and orientation of the ellipses do not change substantially from one subject to another. In contrast, the stiffness magnitude varied considerably. This graphical representation provides a "gestalt" and affords a qualitative understanding of the way in which the hand may interact with forces that could change its posture. Describing hand posture as an oriented stiffness ellipse helps us to determine which of the parameters of postural stiffness are subject to modulation and control by the CNS.

As shown in Fig. 2, the stiffness associated with hand posture varies substantially at different positions of the hand in the work space. Specifically, the shape and the orientation display a common pattern which can be summarized as follows: the stiffness is more isotropic (circular) in proximal positions and more anisotropic (elongated) in distal positions; the direction of maximum stiffness is oriented along a radial line joining the hand to the shoulder. Thus, in a displacement from right to left at constant hand-to-shoulder distance, the stiffness undergoes a counterclockwise rotation.

Several factors may contribute to such regular variations. First, the mechanical advantage of a force applied at the hand is a function of the elbow and shoulder joint angles and, as a consequence, the stiffness observed at the hand would be expected to change for different arm configurations. Second, the muscle tensions are subject to variation in their moment arm as the joint angles change in the work space and the apparent stiffness of a given muscle may change with its length. As a consequence, the contribution of an individual muscle to the total stiffness of the arm is significantly different for different arm positions. Third, since the neural input to the muscles changes their spring-like properties (Gottlieb and Agarwal 1978; Rack and Westbury 1969, 1974), the observed variation in the stiffness may be due to the different levels of neural activation associated with different postures.

When stiffness was recorded in the same subject at intervals of days or months there was a remarkable constancy in its shape and orientation. In contrast, it varied substantially in magnitude (up to 100%). These variations can be attributed either to a change in the level of "arousal" of the subject or to the aftereffects of a prior experimental condition in which the subjects experienced postural disturbances. This variability in magnitude, coupled with the relative invariance in orientation and shape, is a strong indication that the increase in the motoneural activity, which is responsible for the increased magnitude of the stiffness, must be delivered in a well controlled way. A change in stiffness magnitude at constant shape and orientation can be achieved only by a uniformly scaled change in the individual stiffnesses of all the elastic elements. It suggests that the alpha motoneuron activities are subject to coordinative constraints resulting either from coupling among different motoneural pools or from supraspinal signals activating these pools.

Although the observations show that the predominant effect of changing neural input is to change the magnitude of the stiffness, changing the configuration of the arm while the hand remains in a given position has a profound effect on both the shape and the orientation of the stiffness. This suggests that an effective strategy for changing all parameters of the postural stiffness may be to combine changes in neural input to the muscles with changes in the configuration of the "extra," or redundant, degrees of freedom of the limb. Changes in arm configuration will also have a profound effect on other components of the neuromuscular impedance and, indeed, changing arm configuration is probably the only way the CNS can change the endpoint inertia of the limb (Hogan 1984). From this point of view it can be seen that the configuration of the limb should be regarded as one of the "commanding inputs" available to the CNS for controlling posture. The redundancy of the musculoskeletal system is usually regarded as a problem to be overcome by the CNS in coordinating limb movements (Bernstein 1967); instead, the results reported here show that it may offer the CNS alternative ways to control postural dynamic behavior.

To summarize, experimental evidence indicates that the equilibrium position of the hand is established by the coordinated interactions of the elastic forces generated by the arm muscles (Mussa-Ivaldi et al. 1985). According to the equilibrium trajectory hypothesis described first in the context of single joint movements, the hand trajectory of the multi-arm is achieved by gradually shifting the hand equilibrium positions between the initial and final position. In this control scheme the hand tracks its equilibrium point; hence, *torque is not an explicitly computed variable*. This idea is appealing not only because of its simplicity but also because it is fundamentally different from those used to control artificial systems such as a robotic arm. I should hasten to say, in the case of the multijoint system, that the validity of this hypothesis has been demonstrated only through simulation work (Flash 1987).

The model developed by Flash (1987) has successfully captured the kinematic features of measured planar arm trajectories. The simulated trajectories resulted from the interactions between viscoelastic forces and the inertial properties of the arm. The stiffness parameters used in the simulation were derived from experimentally measured postural stiffness value. The observation by Mussa-Ivaldi et al. (1985), that the shape and orientation of the stiffness field cannot be modified by voluntary interrention, provided the justification for assuming that the static value of these parameters may not change when the hand moves through those locations at which the field was measured. The success of the simulation in capturing the kinematic details of measured arm movements is important as a step in providing us with a new intellectual frame for understanding trajectory formation in the multijoint context. The simulation work indicated a control strategy whereby the motor controller may avoid complex computational problems such as the solution of the inverse kinematics and dynamics problems.

Since in the equilibrium trajectory hypothesis position and stiffness are the controlled variables, the problem of inverting the equation of motion (from planned trajectory to the torques) essentially disappears. According to this view, the muscles with their mechanical and geometrical properties seem to be capable of performing the "computation" of torques. The task of the CNS is then to transform the planned trajectory into a sequence of equilibrium positions and stiffnesses.

CONCLUSION

At the present time the problem of how torques are produced is one of the main concerns of investigators of motor functions in artificial and biological systems. In this paper I have reviewed current methods in robotics and put forward a new biological perspective. For the future a number of lines of investigation can be proposed. For instance, there are questions related to the design of limbs and their influence on the structure of the neural controller. Correspondingly, we should, and probably can, search to see whether there are geometrical features of muscle configurations which simplify dynamics. It will also be of importance to examine the motor strategies with studies based on exact quantitative evaluation of trajectories. Beyond this there are many problems of fundamental importance which, because of their complexity, have not yet been tackled by neuroscientists. Examples of these include the question of modular and hierarchical organization of the motor system, the specification of time, and the way in which we use memory both in controlling specialized, highly learned skills and in the solution of novel motor tasks.

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