FINAL POSITION CONTROL IN
PLANAR HORIZONTAL ARM MOVEMENTS

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ABSTRACT

Simplified control strategies based on the concept of "Final Position Control" for free reaching movements of the human upper limb have been simulated in a model incorporating six lumped muscles. The resulting movement repertoires bear some resemblance to normal human movements, but do not provide a complete explanation for observed behavior. The significance of these findings are discussed, and some implications for manipulator control are suggested.

I. INTRODUCTION

The planning and control of movements by a linkage — such as a human limb — is a difficult task. This problem is compounded in biological systems by complex nonlinear properties of the actuators (i.e. muscles). It is therefore appealing to speculate that the nervous system has evolved strategies for simplifying the planning and control problem. This hypothesis suggests that the biocontroller is able to exploit specific properties of the musculoskeletal plant in order to utilize simple controls for generating movements.

Studies of human arm reaching movements have shown that the hand usually follows a straight line path in the absence of other instructions. Curved movements appear to be made by segmentation into relatively straight sections.[1,2] The velocity of the hand in straight movements follows a symmetrical bell-shaped profile.[1] While this scheme may simplify planning of movements, there is no a priori reason to suppose that has advantages for the controller; in fact it may make control more difficult.

It has been suggested that one possible simplified control strategy may be to specify activation levels for all muscles such that equilibrium is established at the desired end point.[3] At the start of movement these activation levels would be set, and the time course of the movement would be determined solely by the dynamics of the actuators and linkage. These arguments depend on consistent spring-like properties of muscles.[3,4] While this scheme is appealing because of its simplicity, it is not clear whether it is sufficiently powerful to explain observed behavior.

We have therefore simulated two degree of freedom arm movements in the horizontal plane using several schemes in which additional constraints are combined with final position control

in order to realize realistic trajectories. Sufficient alternatives have been explored that we believe the conclusions to be true for all such schemes. The results suggest that these strategies *alone* are not suitable candidates for biological motor control, since additional trajectory control is necessary.

II. Methods.

Planar horizontal arm movements in which gravity plays no part have been simulated. A simplified model of the human arm has been developed. The limb segments, viewed as links, are modeled as cylindrical rods. Mass and inertia estimates were obtained from Hollerbach & Flash[5] who used a standard commercially available program (ANSEPA, from BIOMLIB, Postfach 860765, D-8000 Munich 86, West Germany).[6] The kinematics and dynamics are equivalent to a standard two link planar manipulator, except that joint torques are developed by muscles. Six spring-like muscles act at the joints with constant moment arms. There is one pair of antagonistic muscles at each joint, plus a pair that cross both joints, as do biceps and triceps in man. Muscles are modeled as variable stiffness springs, with nervous system activation determining the stiffness. A minimum stiffness corresponding to passive properties is specified for each muscle. Linear viscosity is incorporated. Stiffness and viscosity both scale with activation. Since real muscles do not generate instantaneous changes in force, a simple first order lag with a time constant of 25 msec is used to model the typical 70 msec rise time of a muscle twitch. We believe that if a control strategy is inadequate in this model, it will be even less well suited to controlling real limbs.

A simulation program has been written in Lisp and implemented on MIT Lisp Machines. The dynamics are integrated using a fourth order Runge-Kutta algorithm with a step size of 10 msec. Plots of the resulting trajectories and of joint angles and hand velocities are made using Lisp Machine graphics software. Further details of the programs are available from the author.

III. Choice of inputs to the muscles.

A target point in two dimensions is uniquely specified by the cartesian coordinates of the hand or by the two joint angles. Since there are six muscles in the model additional constraints are necessary in order to resolve this redundancy. Several methods for selecting such constraints and obtaining complete solutions have been tested. For any such strategy more than one feasible solution may exist. In such cases the one which minimizes the sum of muscle forces at equilibrium is chosen. This criterion implies minimum metabolic energy expenditure in maintenance of posture. Linear programming is used in this selection, so that one or more muscles will always be minimally activated.

Strategies for choosing muscle activation are

1. Pure final position control (pFPC). Just the two equilibrium equations are specified. The overall level of activation can be modulated within the simplex by specifying a minimum sum of all stiffnesses (2 equations). There are no constraints on the trajectory itself.

2. Directed acceleration final position control (dFPC). In addition to the constraints specified for pFPC, we require the initial acceleration of the hand to be directed towards the target, encouraging straight line movement (3 equations).

3. Directed stiffness final position control (sFPC). In this case the equilibrium position and the cartesian stiffness tensor at that point are specified (5 equations). The rationale is that a potential energy field with steep walls perpendicular to the desired direction of movement can be created, thereby penalizing deviations from straight line paths.[7] Two-joint muscles should

be especially useful in implementing these controls.

4. Synergical final position control (cFPC). The six muscles are split into two antagonistic synergies, each of three muscles, in whatever manner minimizes total force at equilibrium. The synergical linkages are chosen to generate linearly dependent equilibrium equations, fixing the ratio between agonist and antagonist activation. Consequently the overall level of activation can be adjusted without affecting the equilibrium. This strategy differs from the preceding three in that it forces all six muscle activation levels away from their minima.

There is no explicit way to specify the time of the movement in any of these strategies. Indirect control of movement speed is possible through modulation of overall activation: increased activation results in larger forces, increasing movement speed. In return for this limitation one gains the advantage of an extremely
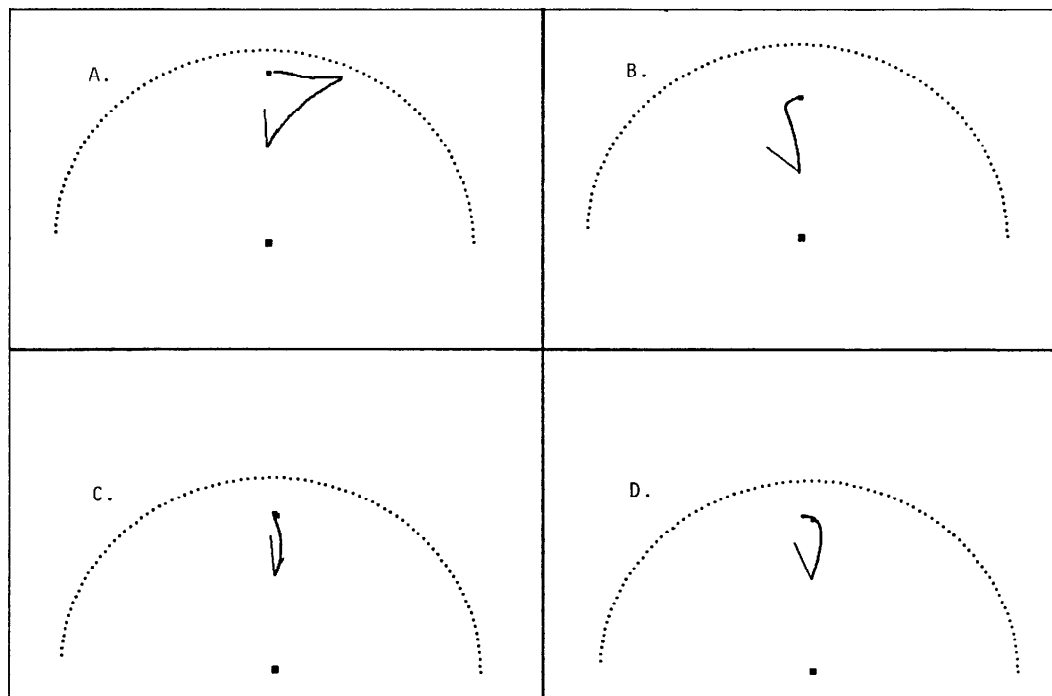

Figure 1. Simulated movements using different single command strategies. A: Pure final position control. B: Directed acceleration final position control. C: Directed stiffness final position control. D: Synergical final position control. In each case the large solid square represents the position of the shoulder joint, and the semicircle is the outer limit of the workspace. The path of the hand is shown. Movements end at the small solid square. Two lines are drawn at the start point: the long line is the direction of initial force at the hand, while the short line (not always visible) is the direction of initial acceleration. All four simulations represent similar movements away from the body of about 20cm extent.

simple control.

IV. Results.

A standard format has been followed in presenting results: only the hand trajectory within the workspace is depicted. Due to space limitations only one characteristic movement is presented for each strategy. In each case a movement starting in front of the shoulder and directed straight ahead is shown.

pFPC (Figure 1A). Movements often deviated considerably from straight line trajectories, and could frequently best be described as "wild". Indirect control of speed through overall activation level was not very successful. Velocity profiles showed minima at reversal points in the movement and at points of high curvature. At best these were much less symmetrical than the prototypes.

dFPC (Figure 1B). Again there was often considerable deviation from straight lines, though some movements were very good. The figure shows one of the better results. The velocity profile was highly assymetrical. There were several points in the workspace at which no set of muscle stiffnesses could satisfy all constraints. Control of movement speed was least successful using this method. However the trajectories were more realistic than pFPC.

sFPC (Figure 1C). Setting the stiffness tensor as described above resulted in straighter movements, often comparable to prototypes. Some movements still displayed high curvature. Velocity profiles were again assymetrical. There were many points in the workspace where the constraints could not be satisfied, and there were severe limits as to how different the eigenvalues of the stiffness tensor could be made (the ratio of eigenvalues determines the steepness of the potential energy "valley"). While a wide range of movement speeds was possible, higher velocities necessitated extremely high levels of muscle activation together with the considerable co-contraction needed to realize the stiffness tensor. If the stiffness levels were made sufficiently large (typically an order of magnitude greater than any seen in human limbs) then movements with minimal curvature could be generated.

cFPC (Figure 1D).

In most cases only one synergy resulted in a feasible solution. The results were not radically different from sFPC: movements were gently curved, velocity profiles were assymetrical and a fair degree of control of speed was possible. There was substantial co-contraction since muscle activation levels were linked. In general the two-joint muscles seemed to be less strongly activated than the others, though this may have been an artifact of the implementation algorithm. Since this synergy trategy takes no account of the starting point, it requires minimum information for its implementation.

V. Discussion.

None of the methods proposed was able to account for observed human behavior. However all did have rich behavioral repertoires, many of which are interesting in their own rights. There were two strategies that required no information as to the starting location (pFPC and cFPC). Although this information is usually available, a strategy of this type would be useful to an organism that had lost sensory feedback — these are essentially open loop motor programs. Since deafferented animals are able to move without visual feedback, the nervous system must have at least one open loop strategy available. The ability to control the form of the trajectory is severely restricted in these

schemes. However there is *no* means by which detailed control of trajectory to a target is possible if the initial state is unknown.

Both sFPC and dFPC attempted to escape from this limitation, in both cases at the cost of increased complexity in determining muscle activation levels. In both cases an additional cost was a reduction of the part of workspace in which the strategy was realizable. This may not be a real limitation, since accurate control of movement may only be necessary in the restricted region in which most manipulation occurs. dFPC was unable to generate reliably straight trajectories. sFPC was considerably more successful in realizing this requirement, but was limited by the poor agreement with hand velocity profiles and the high levels of coactivation of almost all muscles necessary to generate movements at normal speeds.

The results are interesting in the context of manipulator control[7] in that they suggest that strategies such as sFPC may be useful where low precision, computationally inexpensive free movements are required. The most obvious application is in manipulators with tendon actuators. However the kinematic properties of the muscle-like actuators used here may be easily simulated using conventional torque motors or hydraulic actuators. Such schemes are intrinsically compliant, another potential advantage over conventional controls.

In conclusion, "single command" schemes employing final position control are not flexible enough to be a sufficient explanation for upper limb reaching movements. However it is possible that they form part of the overall motor controller, with a superimposed detailed trajectory plan.[8] This form of combined control would simplify the transition from movement to posture. Further insight into that component of arm movements that is a consequence of arm and muscle kinematics and dynamics has been obtained, resulting in improved understanding of the control problem.

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