

Comments on a paper "Strategies for the control of voluntary movements with one mechanical degree of freedom", by Gerald L. Gottlieb, Daniel M. Corcos, and Gyan C. Agarwal

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Strategies for the control of voluntary movements with one mechanical degree of freedom

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same direction, the initial velocity and acceleration traces coincided. Although the relative EMG intensities recorded from several arm muscles depended on movement direction, they followed no systematic trend for different movements with different amplitudes but the same movement direction. The durations of muscular activities, however, did increase with movement size.

Experimental paradigms in which either movement speed or duration was the controlled variable were reported in several recent studies of point-to-point movements (e.g. Flash & Hogan 1985; Hollerbach & Flash 1982) and the velocity and acceleration profiles did obey the kinematic rules defined by Gottlieb et al. for the speed-sensitive strategy. In other studies when accuracy constraints were present, more accurate movements were performed more slowly (Soechting 1984) and movements with larger amplitudes required longer durations (Georgopoulos 1986).

When other accounts of multijoint movements are reviewed, however, two shortcomings of Gottlieb et al.'s approach become evident. The authors have limited themselves to the analysis of experimental paradigms in which the subjects were instructed to control certain task variables. A key question in the analysis of goal-directed motor behavior, however, concerns what kind of strategies the central nervous system uses under less artificial conditions, when the selected behavior is aimed at satisfying certain internal objectives and not artificial constraints imposed by the investigator's instructions.

An example of such behavior can be found in many recent multijoint studies in which the subjects were given no instructions regarding the required speed, duration, or accuracy. Under these conditions, reaching movements of different extents had roughly constant durations. The durations of muscle activities also remained roughly constant while the EMG intensities increased with movement size (Accornero et al. 1984). This so-called isochrony principle is obeyed when subjects perform either simple or complex tasks (Flash & Hogan 1985; Viviani & Terzuolo 1982). Another shortcoming of Gottlieb et al.'s analysis is that their proposed categorization was based mostly on the amount of congruence between the initial parts of the velocity and acceleration traces. Not enough attention was paid to the temporal properties of the entire trajectory. For example, in many accounts of multijoint movements it was noticed that the shape of the velocity profile is invariant under translation, rotation, speed, and amplitude scaling (Hollerbach & Flash 1982). Inertial load also did not seem to affect the temporal and spatial properties of the performed trajectories (Atkeson & Hollerbach 1985). It was shown that such scaling laws hold even when subjects reach for small and large targets, that is, when the target is small an equivalent movement is made to a virtual target located 5% to 8% proximally to the actual target. When the accuracy demands become more stringent, the scaling laws no longer hold (Soechting 1984).

The above analysis therefore indicates that Gottlieb et al.'s approach could be extended to the multijoint case but this would require a more careful examination of movement trajectories and a more flexible definition of task constraints. With regard to the rules obeyed by the EMG signals and excitation pulse, since the generation of even simple two-joint reaching movements involves the activation of many muscles, any attempt to extend the two-strategy approach to the multijoint case would also require a less restrictive definition of the excitation pulse, that is, it should relate to the neural input to a larger group of muscles and not merely to the agonist-antagonist pair.

Moreover, since in the multijoint case the kinematic rules postulated seem to apply not to single-joint movements but to the movement of the hand in extracorporeal space, a more central excitation pulse, which may account for the characteristics of the hand trajectory at the cortical level, should be considered. In this respect, the analogy drawn by the authors between their approach and the model proposed by Adamovitch and Feldman

(1984) for single-joint movements is quite interesting [see their accompanying commentary; *Ed.*]. This model suggests that the velocity according to which the joint equilibrium position is shifted determines the speed of the emerging movement. In a recent model proposed by Flash (1987) it was also hypothesized that the generation of reaching movements may involve a gradual shift of an equilibrium position. Such a control scheme eliminates the need for an explicit computational solution of the inverse dynamics problem. This time, however, it was the hand's, and not the joint's, equilibrium position which was assumed to be shifted (see also Hogan 1985). Moreover, hand equilibrium trajectories were assumed to be spatially and temporally invariant. However, unlike in the model proposed by Adamovitch and Feldman (1984), the speed of the hand equilibrium point was not assumed to be constant but to have a time profile which can be described by the minimum jerk description (Flash & Hogan 1985).

The ideas presented in the equilibrium trajectory model for multijoint movements are consistent with recent physiological findings indicating that the temporal and spatial properties of hand trajectories are represented at the level of neural populations (Georgopoulos et al. 1986). These reports demonstrate that the motor cortex is a key area in the control of the spatial aspects of reaching. The direction of the population vector was found to be closely related to the instantaneous direction of hand motion in extrapersonal space. Although the relations of the activities of single cells to movement amplitude were found to be less frequent and strong (Schwartz & Georgopoulos 1987), a signal related to the instantaneous velocity of the upcoming movement was present in the population discharge. Hence, for multijoint movements regularities that correlate with the temporal and spatial properties of hand trajectories can be sought at the cortical level.

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Strategies are a means to an end

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The target article draws attention to the value of using invariant relationships in motor performance to determine the strategies used by human subjects to control simple movements. Gottlieb et al.'s effort to provide a unifying framework is laudable and their stress on the achievement of accuracy is appropriate. We also agree that trajectory control strategies that require variation in speed may differ fundamentally from those in which duration is varied. We are uncomfortable with several of their assumptions, however, and with their overall perspective regarding the concept of strategy. We will examine here some of these issues and suggest a different framework.

An important assumption made by Gottlieb et al. is that it is possible to infer that subjects used a global strategy merely by documenting the existence of a set of "rules between a . . . task and measured variables" which is "sufficient to perform the task." This definition, however, neglects to consider that such rules can only reflect the use of a strategy when there exist alternative ways to perform the task. It is just as invalid to infer strategy if trajectory control is entirely constrained by the task as it is if the relationship derives exclusively from a mechanical constraint. Thus, to take one of many similar examples of strategies that are cited, Gottlieb et al. characterize our subjects who were instructed to produce trajectories matching those of previously presented waveforms of differing durations (Ghez &

Gordon 1987) as using a "speed-sensitive strategy" (note 18). Variation in speed by these subjects was a simple consequence of obeying instructions: The subjects had no choice; hence, unless the concept is trivialized, they cannot be considered to have selected a particular strategy. The issue of strategy in trajectory control arises only when it can be demonstrated that it is possible to carry out the specific task by alternative means.

Gottlieb et al. also claim that their hypothesis describes how subjects control movements if they "obey" Fitts's law (section 10.1), which, they assert, defines a "speed-accuracy" strategy. Besides relegating their "speed-sensitive" and "speed-insensitive" strategies to the role of tactical implementations, this restriction in the scope of their analysis leads to certain inconsistencies. For example, their subjects do not always obey the speed-accuracy tradeoff function proposed by Fitts (1954) (see below re. Figure 6). Indeed, the specific forms taken by speed-accuracy trade-offs vary with the performance criteria imposed in different tasks (see Meyer et al. 1988), and, as originally formulated, Fitts's law itself applies to conditions in which movements are not self-terminated as are the movements considered here. In Fitts's law, movement time rather than "speed" is the dependent variable, an important distinction since it is generally considered that greater accuracy is achieved by additional "submovements" or corrections (Meyer et al. 1988). These prolong movement time in a way not easily related to movement "speed." Such corrective movements cannot be accounted for by either of Gottlieb et al.'s hypothetical strategies. In addition, taking speed-accuracy trade-offs for granted can easily obscure the fact that different task demands can alter accuracy in quite different ways. For example, when subjects produce force responses of different amplitudes to match unpredictable targets and initiate their responses "as soon as possible," inaccuracy takes the characteristic form of a central tendency bias. We have found that this bias reflects the fact that urgently produced responses are emitted before they are completely specified (Hening, Favilla & Ghez 1988). This type of error is quite different from the simple increase in variability that occurs when subjects attempt to minimize response duration (i.e. force rise time) (Gordon & Ghez 1987).

Another important assumption is that strategy controls an "excitation pulse" which in turn produces EMG and kinematics. Although this idea is appealing, it is misleading to suggest, as is done here, that analysis of EMG allows direct inferences to be made about the intensity and time course of the "net descending presynaptic input . . . which converges and summates within the alpha motoneuron pool." Such inferences are hard to justify because of the multiple indeterminacies involved. First, it is difficult to infer the firing patterns of motoneuron pools from surface EMGs because of the possibility of differential contributions of rate modulation and recruitment, especially at the beginning of a rapid or "ballistic" movement. Second, changes in excitatory drive reaching the motoneuron pool derive not only from the descending supraspinal input but also from changes in afferent input, from gating of reflex connections (Fournier et al. 1983; Hultborn et al. 1987) and from the reciprocal actions of segmental oscillators (Grillner 1981). Third, the fine detail of the EMG bursting patterns in muscles during limb movement is strongly influenced by segmental and afferent mechanisms (Ghez & Martin 1982).

Although the "excitation pulse" is clearly a theoretical construct, Gottlieb et al. frequently write as if it were directly apparent. For example, in their description of Figure 6, they state, "the intensity of the excitation pulse remained constant while its duration varied," implying that the "excitation pulse" is observable in the initial rate of rise of the surface EMG. Similarly, when considering various results, they largely base their determination of strategy on the initial slope of the agonist EMG burst, presumably because this variable is seen as a filtered transform of the "excitation pulse." We would argue that this approach places undue explanatory weight on an

imperfectly sampled variable to tell us whether the intensity or duration of a hypothetical "excitation" parameter is being controlled by the nervous system. Moreover, we have noted that the kinetic variable force rise time may have a constant duration over a range of amplitudes despite the fact that agonist burst durations show small but progressive increases (Ghez & Gordon 1987). For this reason, we have preferred to rely on the specific relationships among trajectory parameters themselves rather than EMG variables to characterize the strategies used to perform a task (Ghez 1979; Gordon & Ghez 1987a).

Gottlieb et al.'s Figure 6 illustrates that the narrow focus on the slope of initial EMG leads to incongruous conclusions. This figure is presented as a canonical example of a "speed-insensitive strategy," used when subjects "move different distances or loads in the absence of additional constraints on movement speed or time or changes in absolute accuracy requirements." Although the authors assert that "movement times are proportional to distance" in this experiment, the data illustrated show that movement times to the first zero-cross of velocity are nearly constant (especially for the middle and large response and in apparent violation of Fitts's law). Rather, it is peak velocity that is proportional to distance (as is also peak acceleration). Thus, we have the paradoxical situation of a subject using a "speed-insensitive strategy" to produce movements in which speed is proportionally modulated to achieve different distances.

Another example of how Gottlieb et al.'s framework can be confusing is seen in their discussion of some of our experiments on the amplitude control of transient isometric forces or force impulses (note 18). We reported that, when instructed to be accurate, subjects who were free to adjust response duration achieved different peak forces by modulating the rate of rise of force while maintaining force rise time near a constant value (Gordon & Ghez 1987a). The authors surprisingly refer to this as a "speed-insensitive strategy," perhaps because we did not instruct our subjects regarding speed or duration. Nevertheless, like their subject in Figure 6, our subjects achieved the goal of the task by modulating the rate of rise (i.e., speed) of the trajectory rather than its duration. Because they focus their analysis on the initial agonist EMG slope, however, the authors insist that, in both cases, the nervous system is primarily modulating a duration parameter. We feel that this stretches the imagination and reflects the conceptual difficulties of the overall framework.

Gottlieb et al.'s framework is ultimately unsatisfactory because the proposed strategies are not defined at the level of the variables and constraints of the task and do not clarify how successful performance emerges. Though a strategy may indeed be represented by a particular set of rules, the function it serves is to achieve a specific task objective with available resources given the constraints presented by the particular task conditions. In the case of the movement tasks considered here, the primary objective of a motor strategy is to control the distance moved or the force produced in the face of a particular set of performance criteria for accuracy, urgency, duration, and so forth. The resources available are two classes of control mechanisms, feedforward and feedback (each with its own costs and benefits) and the information on which they depend. The use of potentially faster feedforward mechanisms is limited by the degree to which available information allows accurate predictions of motor plant and environment. The use of feedback, which may allow greater precision, is primarily limited by delays and the potential for instability. The nervous system is likely to make strategic use of different forms of feedforward and feedback depending on the demands of the task and prior experience.

In our work on the control of simple isometric responses (Ghez 1979; Gordon & Ghez 1987a; 1987b), we have found that by distinguishing control over the rate of rise of force from control over the duration of the change in force it is possible to

identify the separate contributions of feedforward and feedback control even within smooth trajectories. When subjects produce impulsive trajectories to a range of targets whose amplitudes vary unpredictably, the initial rate of rise of force is scaled to the target as well as to the final force achieved. In contrast, force rise time appears to be maintained around a fixed value. This indicates that subjects use predictive mechanisms and feedforward control (Gordon & Ghez 1987b). We have referred to this mode of trajectory control as "height control," to differentiate it from "width control," where duration varies in proportion to amplitude or where initial trajectory parameters are independent of target. (The terms "height" and "width control" are borrowed from the oculomotor literature (Bahill et al. 1975a; Robinson 1975) and seem more intuitive than the related notions of speed "sensitivity" and "insensitivity.") Width control frequently occurs when subjects attempt to achieve a new steady state force rather than a transient or impulsive trajectory (Cordo 1987; Hening et al. 1983); the operation of feedback mechanisms or of successive corrections must then be considered. More generally, however, the degree of predictability of targets, the urgency of responding, the structure and experience in a particular task, and a variety of other factors all influence the nature of the errors that subjects make and determine the mix of predictive and feedback control they use. In sum, we would suggest that a theoretical analysis of motor strategies is possible only when there are alternative means for performing a motor task. Such an analysis seems useful only if it clarifies the operation of neural mechanisms for processing information to control movement trajectories.

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If a particular strategy is used, what aspects of the movement are controlled?

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Gottlieb et al.'s central hypothesis is that movements are planned according to two strategies, a speed-insensitive (SI) and a speed-sensitive (SS) one. The SI strategy is defined as one in which "EMG rises at the same rate irrespective of changes in distance or load." This strategy predicts specific velocity and acceleration profiles. However, the predictions of the SS strategy are not specific at all. In our view the SS strategy is rather loosely defined in saying that "intensity is modulated" and that "duration (of the excitation pulse) may change in the same or the opposite direction." In fact, any strategy that is not an SI strategy, belongs, by definition, to the SS-type class. The SS strategy therefore lumps together all movement strategies other than the SI strategy; and the fact that these two strategies suffice to explain all the experimental data is not surprising at all, but rather a result of the definition of the two strategies.

Gottlieb et al. confine themselves to movements in a joint with a single degree of freedom. It is worthwhile to stress, however, that the same control strategies are also observed in movements with more than a single degree of freedom, such as handwriting (Denier van der Gon & Turing 1965), drawing and playing musical instruments (Denier van der Gon 1979). In our view, single-joint movements are an artefact of the experimental protocol and are just a rare sample from the whole repertoire of normal movements. Furthermore, such multijoint movements can be performed similarly and perfectly well without visual information, suggesting that the control mechanisms under

discussion are part of the motor program and not due to visual feedback mechanisms.

An interesting question, which is not addressed by the authors, concerns *what* is controlled during the movement: the precise movement trajectory, duration and amplitude of muscle force, or the EMG muscle activation pattern. In our view the answer is very relevant for the mechanisms thought to underlie motor programming. Gottlieb et al. assume that muscle force is controlled. However, the force-velocity relationship, which causes a significant decrease of muscle force at constant activation for forearm flexion velocities of 0.5 m/s and higher (Jorgensen 1976), the Coriolis forces, the position-dependent inertia and mechanical advantage of muscles, the effect of muscle nonlinearities related to previous activation or muscle length prior to activation (Abbott & Aubert 1952) – all of these factors make it virtually impossible for the nervous system to control muscle force or movement amplitudes and velocities using the simple laws of mechanics. These problems may seem hard to solve for single-joint movements; the complexity increases even more for the control of multijoint movements.

Goal-directed movements to stationary targets in 3-D space start immediately in about the correct direction (van Sonderen et al. 1988). This suggests that muscle activations for fast movements are set and tuned to each other *before* the onset of the movement. Because of the low-pass properties of muscle (time constant of arm muscles is 50 to 100 ms), modulation of muscle activity is not a very effective mode of movement control after movement onset to compensate for changes in muscle force due to the force-velocity and force-length relations and due to the dependency of muscle mechanical advantage on joint angle. It therefore seems reasonable to assume that the intensity of the first agonist burst is generated open-loop and is constant for the relatively fast movements that form the data base in Gottlieb et al.'s target article. The setting of the intensity of muscle activation may depend on the intended movement velocity or duration. On the other hand, modulation of the duration of muscle activation is very effective. This is evident from vibration experiments (Sittig et al. 1985; 1987) showing that vibration-induced afferent information has no effect on the accelerating forces of moderately fast movements but clearly affects the duration of the movement. Also, variability in the initial acceleration of a set of movements with the same duration and the same amplitude are compensated for by the duration of the acceleration (van der Meulen et al. 1988).

Similar observations have been made with targeted force impulses in isometric contractions (Gordon & Ghez 1987b). Our suggestion (which is not necessarily incompatible with Gottlieb et al.'s view) is that the subject makes a rough choice of a level of excitation for the muscles depending on the intended movement velocity. When the excitation level is set, the duration of agonist activation and the onset of the antagonist activity are determined in our view using an internal model of the task and the limb, just as in the control of saccadic eye movements (Scudder 1988; van Gisbergen et al. 1981). Due to transport delays in the afferent and efferent pathways, afferent information may be used only in later phases of the movement, presumably in the decelerating phase.

From these considerations it follows that it is not at all clear that two strategies are necessarily used. It may just as well be one strategy: selecting what muscle activation is appropriate for the task with variation of the duration based on the internal model of the limb and of the task.

The issue of different strategies may arise with regard to some other aspects of movement control, however. Sittig et al. (1987) have shown that subjects may use different aspects of the afferent information (position or velocity information) during movements, depending on the instructions and the type of movement. These observations seem to suggest that velocity information is used in some types of movement whereas position information is used in others. Moreover, the activation of the