REVIEW PAPER

Theories for Skilled Limb Movements

Gyan C. Agarwal

Dept of Electrical Engineering and Computer Science
College of Engineering, The University of Illinois, Chicago, IL 60607

ABSRACT

Some of the theories that have been advanced to perform skilled limb movements are reviewed in this paper. The aspects discussed in brief include alpha-gamma control, choice of control variables in limb movements, equilibrium point hypotheses, experimental observations from simple movement studies and explanations proposed, in particular the dual strategy hypothesis. The single mechanical degree-of-freedom movements may be controlled by one of two strategies: a speed-insensitive strategy or a speed-sensitive strategy. The term strategy implies a set of rules which specify in terms of task variables and subject instructions how to choose the excitation signal, the controlling signal at the alpha motoneuron level. The two strategies differ in that speed-insensitive strategy is a result of duration modulation of the excitation pulse, whereas the speed-sensitive strategy is a result from amplitude modulation. Finally, the problem of multi-degrees of freedom movements and the role of higher motor control centres are discussed in brief.

1. INTRODUCTION

The human motor system possesses apparently redundant degrees of freedom for performing simple voluntary movements. The existence of some general rules for controlling a limb applicable to any specific type of movement would simplify the task of generating appropriate control signals. To postulate their use is to presume that in making simple, learned movements, the nervous system does not consider every possible way to move a limb from one position to another, but merely selects a nominal control pattern or set of control rules from memory in the form of a motor program or schema[1,2], which requires only a few parameters to satisfy the specific elements of the task. This notion is quite congruent with Bernstein's concept[3] of 'synergies' or 'units of movement'. Such schemes or theories of motor control are, however, abstract. Providing convincing evidence for specific rules and defining the controlling parameters has proved elusive[4]. This is in no small measure because there are almost certainly more than one set of rules. Furthermore, there is no generally

accepted method in the motor control literature by which rules can be stated, tested and compared.

Voluntary movements emerge from wnat a person 'wants to do', which in experimental circumstances is, at least in part, what a person has been instructed to do. Movements are also influenced by external, objective factors, known or assumed by the person performing them. Constraints may be added concerning specific conditions for movement speed, duration, or end-point accuracy. All these various factors may or may not be compatible with each other.

The objective factors to which we refer, we shall call task variables. These may include the distance the subject is asked to move, the size of the target either imagined or shown to the subject, the time interval over which the subject is instructed to complete the movement and any external load. Given a defined task, a subject is left choices which determine important details concerning how to activate agonist, antagonist and synergistic muscles.

Although in general choices include which synergistic and antagonistic muscles to activate (the problem addressed by Bernstein[3]), this review will be restricted to choices which concern how the dominant agonist and antagonist muscles are activated to produce patterns of force for a single degree-of-freedom movement. Even in this simple situation, patterns of forces and therefore muscle activation can still be made in an infinite number of ways when we regard 'trajectory' as the description of the joint angle and its derivatives over the time course of the movement.

A task usually specifies only a few parameters about the trajectory, such as its starting point and a target region, but not every point at every instant of time. In principle, the subject may choose parameters not explicitly specified, such as the average or maximum speed of the movement, the percentage of time accelerating and the specific final position within the target region. Precisely how much choice a subject has in making a movement (and still following the instructions) is not at all clear. There may be greater freedom in choosing how to activate the agonist, when a limb is starting from a resting position, than there is in choosing how to activate the antagonist which must also deal with the kinematic consequences of the preceeding agoinst activity.

In this paper, some of the theories that have been advanced to perform skilled limb movements are reviewed. Alpha-gamma control, choice of control variables in limb movements, equilibrium point hypotheses, experimental observations from simple movement studies and explanations proposed, in particular the dual strategy hypothesis are briefly discussed. The single mechanical degree-of-freedom movements may be controlled by one of two strategies: a speed-insensitive strategy or a speed-sensitive strategy. Finally, some problems concerning multi-degrees of freedom movements and role of higher motor control centres are discussed.

2. ALPHA-GAMMA CONTROL

Fritsch and Hitzig's 1870 discovery of the electrical excitability of the motor area established one of the pathways to control muscular activity, that is a direct input to the alpha motoneurons and control of muscle activation via alpha motor fibers. Sherrington termed this as the final common pathway to the muscle. The concepts of neurophysiology for control of movements

have been reviewed by Granit[5] and Brooks[6]. The sense organs of the muscles have been shown to measure muscle length, active muscle force, rate of change of muscle length and possibly rate of change of force. In addition, receptors located in joints provide information about joint angles, and receptors located in skin provide information about touch and environment conditions. How this information from various muscles (agonists-antagonists and synergists) is integrated with information from other sensory organs including visual feedback to control movements has been a difficult problem.

Learned tasks requiring a sequence of submovements are produced by complex motor programs that create smooth, fast, coordinated, skillful actions. Various feedbacks are an integral part of such complex motor programs which continually modify these motor commands to achieve the desired goal. Some of the feedback mechanisms form automatic control loops. Sherrington and his colleagues had established the stretch reflex as a negative feedback system for the maintenance of joint position.

The discovery of gamma motor control by Leksell in 1945 added a new and important degree of control over the sense organ itself, a scheme not commonly used in man-made control systems. Merton's hypothesis proposed in 1953 of follow-up-length mechanism for control of voluntary movements was based on the assumption that by contraction of the intrafusal muscle fibres (muscle fibres of the muscle spindle organ) under gamma activation, the extrafusal musculature is forced by the stretch reflex to follow-up until muscle spindles are silenced again. Such a follow-up-position servomechanism is used in many modern control devices, such as power assisted steering and power assisted brakes in an automobile. However, due to insufficient gain across this servo loop and long conduction delays along nerve fibres (Fig. 1), this concept was modified to alpha-gamma linkage meaning that the movements are servo-assisted rather than servo-controlled by the feedback loop. The transport lag from periphery to spinal cord (of the order of 10-15 ms for human leg muscles) is partly compensated by the velocity feedback information from primary spindle organs. Co-activation of alpha and gamma motor inputs provides direct as well as feedback control of the muscular activity. Although it is likely that very fast movements may be carried out by direct alpha
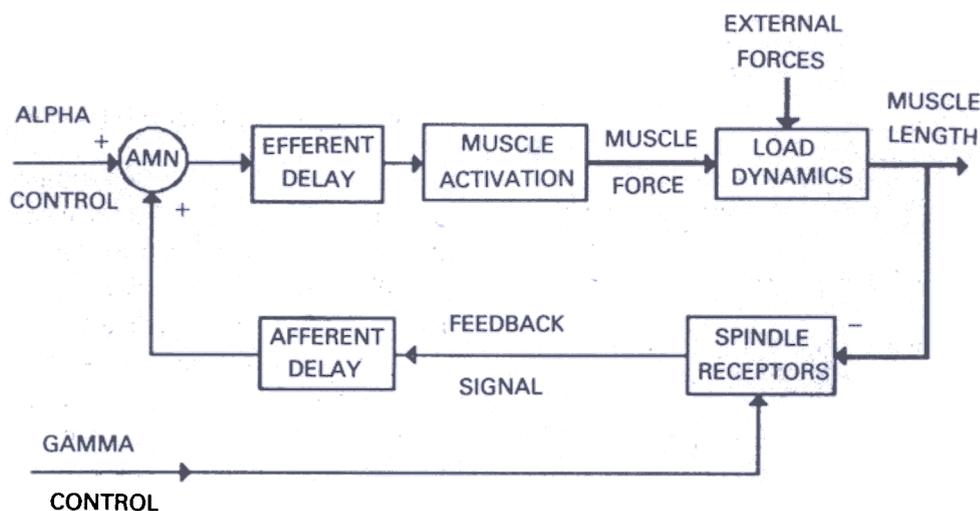
Figure 1. Block diagram of the length control feedback system.

activation, the system must sacrifice accuracy, if the load dynamics is unknown.

3. CONTROLLED VARIABLES IN LIMB MOVEMENTS

To apply concepts from control theory to control of movements, one must clarify the structure of the system, the external inputs, the controlled variables, and the measured internal variables which may be used by the central nervous system controller to generate appropriate control inputs. Unfortunately, this has been one of the difficult problems[4]. This difficulty in identification of the motor system has been partly due to the fact that in human studies our ability to measure the intermediate variable is very limited. Only during the last 25 years acceptable recordings from pyramidal tracks and other central locations have been possible in freely moving animals.

For controlling the movements of a limb, some possible choices for controlled variables are muscle forces, muscle lengths, velocity of movement, stiffness of the joint, etc. Stein[4] has reviewed this literature and concluded that different physical variables may be controlled depending on the type of limb movement required. The segmental reflexes from muscle receptors can overcome some nonlinear properties of the muscle. As a general property, feedback tends to linearize a system. The activation of antagonist in a single joint movement as well as differential activation of synergists and modifications of reflex arc is an adaptive process. Some movements are based on system models and are

largely open loop, such as eye movements because of load invariance.

4. FEEDBACK AND FEEDFORWARD IN MOTOR SYSTEM

The terms feedback and feedforward are often used in the motor control literature. Frequently, these terms imply concepts different from those normally accepted in automatic control literature. The term feedforward has been used for both predictive control and error correcction. Before considering the meaning of feedforward in automatic control literature, we need to be clear as to what is meant by feedback. In general, whenever a closed sequence of cause-and-effect relationship exists among the variables of a system, feedback is said to exist[7]. The feedback affects the overall gain, system stability (i.e. location of closed loop poles in a linear system), sensitivity to individual parameter variations, as well as the influence of external disturbance or noise. In nonlinear systems, enclosing a nonlinearity in a feedback loop, in general, tends to linearize the system[8].

If disturbances are measurable, feedforward control is a useful method of cancelling their effects upon the system output. By feedforward control, we mean control of undersirable effects of disturbances by approximately compensating for them by generating corrective inputs, before their consequences materialize in the output signal. This is advantageous because, in a usual feedback control system, the corrective action starts only after the output has been affected. Such an
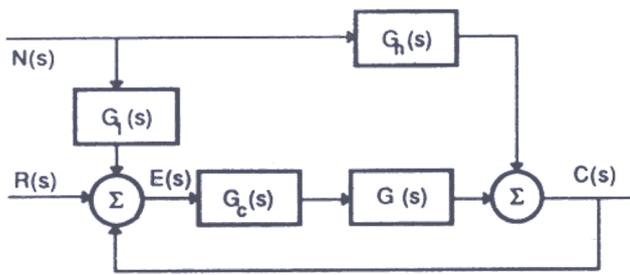
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Figure 2. Schematic diagram illustrating the concepts of both feedback (left-going arrow) and feedforward controls.

application of feedforward is shown in the control system diagram in Fig. 2. In this, we assume that the disturbance $N(s)$ is measurable and acts upon the system output through its transfer function $G_n(s)$. Symbol s stands for Laplace transform variable and we have assumed system linearity to discuss this issue in transfer function notation. Here, $G(s)$ represents the system transfer function. Both $G(s)$ and $G_n(s)$ are fixed. A suitable controller $Gc(s)$ is designed to get the desired overall characteristics of the system. The output $C(s)$ is given by the Eqn (1).

$$C(s) = \frac{G_c(s)\,G(s)}{+\,G_c(s)\,G(s)}\,R(s) +$$

$$\frac{[G_c(s)\,G(s)\,G_1(s) + G_n(s)]}{1 + G_c(s)\,G(s)}\,N(s) \qquad (1)$$

A feedforward correction term $G_1(s)$ can be calculated to cancel the effects of disturbance $N(s)$. If we choose $G_1(s)$ as

$$G_1(s) = \frac{G_n(s)}{G_c(s)\,G(s)} \qquad (2)$$

the effect of $N(s)$ can be totally eliminated in this ideal case. Feedforward control can also be used to minimize the transient error[9].

Since feedforward control is an open-loop control, there are limitations to its functional accuracy. Feedforward cannot be relied on for error correction. Feedforward control does not cancel the effects of unmeasurable disturbances under normal operating conditions. It is, therefore, necessary that a feedforward control system includes a feedback loop to compensate for any imperfections in the functioning of the feedforward control and to provide for corrections for unmeasurable disturbances[10]. It is finally worth mentioning that feedforward should not be used as a

substitute for planning or anticipation which goes into generating the controlling signal $R(s)$.

5. EQUILIBRIUM POINT HYPOTHESES

The control of even very simple limb movements represents a formidable engineering analysis problem with many degrees-of-freedom in the choice of controlling signals. Over the years, many concepts or theories have been advanced to simplify this problem for the purpose of analysis as well as for understanding the underlying mechanisms for control of movements. A concept of equilibrium point hypothesis was put forward by Feldman in 1965. Later, a modified equilibrium point concept was advanced by Bizzi. The original version, known as the lambda model, is based on central parameterization of reflexes as a basis for voluntary movements[11]. The modified version is known as the alpha model[12].

In the Feldman model, the control of voluntary movements is coupled with setting the threshold lambda of the stretch reflex. In the Bizzi model, the control is coupled with setting the level alpha of muscle activity. Both the models belong to a class of mass-spring models that are derived from the observation that in certain tasks the muscular system behaves in a way that is qualitatively similar to a physical system, such as a spring with an inertial load.

According to Berkinblit et al[11] the lambda model has the following assumed properties:

(a) The definition of equilibrium point based on the static characteristics of the lambda model refers not only to statics but also to dynamics,

(b) A shift in the equilibrium point elicits modifications of muscle activity but not vice-versa,

(c) To execute a voluntary movement, the nervous system selects a new reflex threshold that results in a shift of the equilibrium point. Thus, a shift in the equilibrium (postural state) of the system gives rise to a movement, and

(d) Movement velocity may depend on the speed of the shift of the equilibrium point specified by central commands.

The lambda model is based on the static invariant characteristic curves which were measured by successive unloading of a voluntarily contracted limb. However, this description is incomplete and if one looks at both the loading and unloading properties of an activated

muscle, the nonlinearities in length- tension properties of muscle become obvious[13,14]. The proponents of the lambda model assume that the originally formulated model for a single joint unidirectional movements would also apply to more complex single as well as multi-joint movement sequences. This generalization does not follow from any consideration of the laws of physics nor from any convincing evidence obtained from the study of movements.

The experimental evidence for the alpha model of Bizzi et al[12] was obtained from deafferented animals (mainly monkeys) assuming that no adaptation takes place due to loss of afferent inputs. Some recent evidence to support their model has been obtained from spinal frogs. Bizzi et al have pointed out that one major weakness of the equilibrium-point hypothesis is that it is difficult to test. They write: 'Much of the difficulty of arriving at a confirmation (or disconfirmation) of the equilibrium-point hypothesis stems from the problem of defining a (perhaps artificial) boundary between central and peripheral processes[12]'. Such a boundary is non-existent. It is well established that the central processes interact with the peripheral system through gamma input to modify spinal threshold and through interneurons and presynaptic mechanisms to modify reflex arcs.

The veracity of equilibrium point formulations is not yet the unassailable truth, its advocates would have us believe and is in need of greater experimental support. In particular, it is in need of experimental support for its ability to describe: (i) phasic movements, (ii) movements associated with external perturbations and the EMGs which accompany them, and (iii) how to account for the relative contributions of afference in muscle groups with as diverse sensory representation as the soleus and the eye.

6. SPEED-ACCURACY MODELS

The study of movements is a multi-disciplinary field with significant contributions from neurophysiology and, engineering, including biomechanics and psychology. The interaction of speed of movement and its accuarcy has been a focus of psychology studies for nearly 100 years. Many accounts have been presented concerning the relationship between movement speed and movement accuracy and the mechanisms which underlie this relationship[15]. The most widely discussed is the speed-accuracy trade-off formulated in logarithmic form by Fitts[16] and Fitts and Peterson[17].

The speed-accuracy trade-off describes how subjects who are asked to make accurate and fast movements to a target will vary the speed and duration of their movements according to both distance and accuracy requirements. Subjects choose to move more slowly to small and near targets than to large and distant ones. The combined effect of distance and target size upon movement time, which is known as Fitts' law, defines what may be called a 'speed-accuracy' strategy:

$$MT = a + b \log_2 \left[\frac{2D}{W} \right] \tag{3}$$

where MT is average movement time; D is movement distance; and W is the width of the target to which the movement is made. The parameters a and b are empirically determined constants. This behaviour is spontaneous and is an example of how subjects use a strategy for coping with instructions which appear to specify incompatible goals. Subjects are not told to slow down for small or near targets but tend to do so, although instructed to move as rapidly as possible and yet also to be accurate.

Several alternative hypotheses have been proposed for the speed-accuracy trade-off. A deterministic iterative corrections model was proposed by Crossman and Goodeve[18]. They argued that movements intended to hit a target region quickly and accurately consisted of several discrete submovements made in rapid succession. These submovements satisfy three assumptions: (i) each submovement travels a constant prop ion (p) of the distance between its starting location and the centre of the target, (ii) each submovement takes the same constant amount of time regardless of the distance, and (iii) sub-movements are guided by sensory feedback and the submovement sequence continues until the target region has been reached. Let x_k represent the distance to be covered after the kth submovement, then

$$x_k = (1-p) x_k$$

where $x_0 = D$ $\tag{4}$

This discrete equation leads to:

$$x_k = D (1-p)^k \tag{5}$$

The elapsed time t measured from the initiation of movement after k submovements is $t = k\,dt$. Thus, from Eqn (5), we get:

$$x(t) = D(1-p)^{t/\delta t} \tag{6}$$

and taking the logarithms

$$t = \delta t \, \log_{(1-p)} \left[\frac{x}{D} \right] \tag{7}$$

In Eqn (7), the logarithm term is to the base $(1-p)$. Crossman and Goodeve estimated that the submovement time is 100 ms and p is 0.5. This is a form of Fitts' law and has an information rate of 10 bits/s for $\delta t = 100$ ms.

A number of recent studies have shown that the deterministic, iterative-corrections model is seriously flawed. The submovements do not travel a constant proportion of the remaining distance nor are their times constant[19]

Schmidt et al[20] have described movement conditions in which the trade-off is linear rather than logarithmic. They had subjects which made single aimed tapping movements whose distances and durations matched specified target values. They showed that the variable errors in movements (measured in terms of the standard deviation of the movement endpoint) was linearly proportional to the average movement velocity, i.e.,

$$S = A + B \left[\frac{D}{MT} \right] \tag{8}$$

where MT is the mean movement time and S is the standard deviation of the final movement position. These observations led them to a new theory, called the Impulse Variability Model[20] based on several assumptions: (i) rapid movements in the time matching task are generated by a pulse of force that has a selected amplitude and a specified time parameter, (ii) the amplitude and the time parameters are stochastic variables, and (iii) the variability, or noise, in the amplitude and time parameters obeys Weber's law, that is, the standard deviations are proportional to their mean values. Although supporting evidence has beed presented in several reports, questions have been rasied over the logic of the formal theoretical derivations[21].

A stochastic optimized submovement model has been presented by Meyer et al[19]. They first consider the time-minimization task, which involves either one or two submovements. The first movement is the primary submovement, and if it is unsuccessful, a secondary submovement is made. The primary submovement is aimed at the centre of the target region in a time-minimization task. If the primary submovement lands within the target region, W, then the action terminates. The noise in the motor system affects the primary submovement and may cause it to either overshoot or undershoot the target. Meyer et al also assumed that the effects of motor noise increase with the average velocity of the submovements, that is, if the primary submovement travels a mean distance D_1 in mean time T_1, then the standard deviation S_1 of the endpoint is given by:

$$S_1 = KV_1 = K \left[\frac{D_1}{T_1} \right] \tag{9}$$

Similarly for the secondary sub-movement

$$S_2 = KV_2 = K \left[\frac{D_2}{T_2} \right] \tag{10}$$

It is assumed that the average velocities of the primary and secondary submovements are programmed to minimize the average total movement duration $T = T_1 + T_2$. Meyer et al[19] found that the minimum time T is given by the Eqn:

$$T = A + B \sqrt{D / W} \tag{11}$$

where A and B are non-negative constants. Meyer et al extended this model to include cases where n submovements are required. Although increasingly complex models have been suggested, all such speed-accuracy models are all kinematic type and do not consider the dynamic aspects of limb mechanics or of muscle force generation.

7. EMG AND KINETIC OBSERVATIONS FROM SINGLE JOINT MOVEMENTS STUDIES

Waters and Strick[22] and Mustard and Lee[23] found that for fast, accurate movements to a target, voluntary activation of the antagonist muscle was conditioned upon whether the subject halted the movements by actively decelerating the limb, or had them halted by impact on a mechanical stop. For movements halted by impact, attempting to relate antagonist muscle activity to task variables, such as target distance or size or load, or to measured variables, such as peak velocity, was concluded to be inappropriate because the patterns of muscle activity are dependent on a subject's movement 'strategy'[22].

The influence of task variables on movement strategy can be easily shown by observing what happens

when subjects are asked to move from an initial position and accurately stop in a target zone, without more explicit constraints upon movement speed or duration than to move quickly. If the distance to be moved is increased, subjects will usually reach higher peak velocities[24]. If the inertial load is increased, subjects will reach lower peak velocities[25]. In both cases, the movement time will increase. These changes occur in the absence of any explicit instruction concerning speed or movement time.

If a subject is presented with a narrow line instead of a broad band for a target, the speed-accuracy strategy cannot be applied in a straight-forward manner, because W is undefined. Freund and Bundingen[26] used such a target, requiring an accuracy of 10 per cent of target distance. When W is a constant fraction of D, Fitts' Law predicts constant movement times. Freund and Bundingen[26] formulated a *speed-control hypothesis* for the fastest goal directed voluntary contractions from their experiment which is simply: $MT = c$, where c is an empirically determined constant. Freund and Bundingen used two rules describing a 'pulse' of myoelectrical activity for such movements: (i) the duration of the agonist EMG burst determines the movement time, and (ii) the intensity of the EMG is proportional to distance.

Ghez's[27] *pulse-step model* is similar to that of Freund and Bundingen. The main difference is the inclusion of a 'step' component to control the final force, a component which is usually significant in isometric contractions but is ignored for non-isometric inertially loaded movements. More recently, Ghez and Gordon[28] have shown that the area of the agonist EMG burst is dependent on the peak force, but independent of force rise time, whereas burst duration varies with both peak force and rise time. The EMG duration is also influenced by instructions concerning accuracy.

Based upon studies of Schmidt *et al*[20] and others, Wallace[29] formulated the *impulse-timing theory* to describe the way subjects control both distance and movement time in a coordinated way. This theory has four postulates:

(a) The duration of the initial agonist burst and onset time of antagonist activity will be positively related to the total movement time,

(b) The ratio of the duration of the initial against burst to the total movement time and onset time of

antagonist activity to the total movement time will be unaffected by changes in movement distance, movement time, or inertial load of the movement,

(c) The intensity of the initial agonist and anatgonist burst will be positively related to the peak velocity of the movement, and

(d) The intensity of the initial agonist burst will be positively related to changes in inertial load when the movement velocity is held constant.

The rules of this theory deal with movement distance, time and velocity and also with effects of load (based upon work by Lestienne[30]). They are consistent with the conclusions drawn by Freund and Bundingen[26].

One of the problems with the way in which these postulates are stated is that they are not formulated in terms of independent and noninteracting variables. As a result, Wallace's postulates (c) and (d) are conditional and require holding one variable constant. This can lead to ambiguities in predicting behaviour. Even postulate (a) does not imply causality. Long movement times cannot cause prolonged agonist bursts since the agonist burst, ends well before the movement itself. Long agonist bursts cannot cause long movement times, since EMGs are consequence of muscle excitation, not causes of muscle contraction. One must infer more precise meanings.

8. OPTIMAL CONTROL MODELS

Some recent work on rapid limb movements has taken an optimal control theory approach to minimizing various performance indices. Nelson[31] modelled the human limb movement with one degree of freedom. The displacement x of a mass m with instantaneous velocity v is governed by the equations of motion given by:

$$\frac{dx}{dt} = v \; ; \; M \frac{dv}{dt} = f_a(t) - \beta v \qquad (12)$$

where b is the viscous force coefficient, the dissipating force is assumed to be a linear function of the velocity v, and $f_a(t)$ is the net muscle force applied along the direction of movement. These equations of motion may be written in normalized form as:

$$\frac{dx}{dt} = v \; ; \; \frac{dv}{dt} = u(t) - bv \qquad (13)$$

The force $u(t)$ is assumed to be bounded by a maximum value U, i.e. $u(t) \leq U$. The boundary conditions on Eqn (13) are assumed to be: $x(0) = v(0) = v(T) = 0, x(T)$

= D. Nelson[31] considered five performance objectives to derive the controlling input u(t) and the system trajectories. The cost functions considered were: minimium time, force, impulse, energy, and jerk. The minimum jerk cost function was proposed by Hogan[32]. For a double integrator plant with bounded input, the optimization problem for various performance indices has been examined in several studies[33]. For the elbow joint movements, the moment of inertia of the forearm about the elbow axis is estimated to be 0.06 kg m^2(ref 34). The maximum isometric torques for an average subject in flexion and extension directions are about 60 N.m and -46 N.m, respectively. Thus, the normalized torque U (torque per unit inertia) for flexion and extension is about 1000 and 767, respectively.

If the damping parameter, b, is neglected, the acceleration corresponds to the input force per unit mass, u(t). The minimization of the movement time, T, for a given D and U or maximization of the moveme⁻ distance, D, for a given T and U all be determined geometrically. The minimum time solution is the classical bang-bang solution with inputs u(t) = U for 0 ≤ t ≤ T/2 and u(t) = − U for T/2 ≤ t ≤ T. The minimum time for this solution is given by:

$$T_{min} = 2 \sqrt{D / U} \tag{14}$$

and the maximum distance

$$D_{max} = \frac{UT^2}{4} \tag{15}$$

For U = 1000 (and assuming symmetrical flexion and torques) and D = 60°. (= 1.047 rad), the minimum movement time from Eqn (14) is about 65 ms. This number is clearly far from the minimum movement time values of about 200 ms.

The peak velocity and peak acceleration for various optimal control models for given values of movement distance D and the movement time T compare reasonably well Table 1

The ratio of peak average velocity in elbow movements has been calculated in several experimental studies. Ostry et al[35] have reported a velocity ratio range in rad/s of 1.45 to 1.48 in fast continuous flexion movements and a range of 1.85 to 2.12 in fast discrete flexion movements (for extensions these ratios ranged from 1.49 to 1.55 in continuous, and 1.87 to 1.94 in discrete movements). All these numbers are within the theoretical range for various optimal criteria Gottlieb et al[36] reported a similar range of peak velocity in flexion movements and acceleration peaks to 157 rad/s^2 = 9000°/s^2). From Gottlieb et al[36] (refer Fig. 1 on page 343), an estimated jerk value is 3,140 rad/s^3 (= 180,000°/s^3).

The Nelson model is a classic control problem with a bang-bang solution for minimum time movements[37]. This can be interpreted as biphasic muscular activation, that is, a pulse of agonist muscle force accelerates the limb towards the target, and at the midpoint of the trajectory the the antagonist muscle force decelerates the movement at the desired target distance. The concept of bang-bang control of muscular activation based on optimal control theory has been suggested in several reports[38].

Single-joint, discrete movements of a limb, such as the forearm rotating in the horizontal plane about the elbow, possess a surprisingly rich diversity of behaviours. How are such movements organized and performed? Because the muscular forces cannot be directly measured in human subjects, most studies have compared electromyographic signals under various experimental conditions. The optimal control models assume that u(t) represents force; however, there is no one-to-one correspondence between the instantaneous EMG and muscle force in dynamic contractions[39]. Isolated muscle and human studies show that the muscle force cannot be turned on or off in discrete pulse form. There is at least a first order dynamic between the muscle EMG and the force produced in rapid contractions. The limb dynamic models must be modified to include muscle activation. One significant shortcoming of all the optimal control models is their inability to predict the speed-accuracy trade-off because of their deterministic nature.

Table 1. A comparison of peak velocity and peak acceleration values

Criterion type	Peak velocity/(D/T)	Peak acceleration/(D/T$_2$)
	2	4
	1.5	6
	1.875	5.774

9. NUMBER OF SWITCHINGS IN CONTROL SIGNAL

There are disagreements in the literature concerning whether the EMG signals are biphasic or triphasic (i.e., one or two switchings in the control signal) and also concerning the EMG magnitudes and pulse widths for the agonist and antagonist muscles and their relationship to kinematic data, such as movement distance. Some investigators report constant EMG activation duration for different distances; others find that it varies with distance. Some studies show triphasic patterns of EMG; other studies do not[40].

Let us re-examine the biphasic EMG problem using a modified Nelson model and the time-optimal control theory problem with different boundary conditions. A reduced Nelson model (with $b = 0$ in Eqn 13) is given by:

$$\frac{dx}{dt} = v(t) \; ; \quad \frac{dv}{dt} = u(t) \tag{16}$$

Because $u(t)$ in Eqn (16) represents force and the rate of change of force that a muscle can produce is bounded, there will be no discontinuities in force. We will assume this rate to be bounded:

$$\left| \frac{du}{dt} \right| \tag{17}$$

The continuity constraint on $u(t)$ can be incorporated in the model of Eqn (16) by defining a new state variable $f(t)$ for force and a new control input $u(t)$, which is the neural input to the muscle (in appropriate units) which is bounded. With these modifications, our system model is given by:

$$\frac{dx(t)}{dt} = v(t) \; ; \quad \frac{dv(t)}{dt} = f(t) \; ; \quad \frac{df(t)}{dt} = u(t) \; ;$$

$$|u(t)| \leq U \tag{18}$$

Although the relationship between the input to the muscle $u(t)$ and the force output of the muscle $f(t)$ is unknown and is likely to be nonlinear, this equation represents the simplest possible situation. The minimum time problem may now be solved using the maximum principle[37]. Agarwal et al[41] have shown that the number of switchings N for the model in Eqn (18) is given by:

$$N = n - 1 - m \tag{19}$$

where n is the number of state variables, $m = 2n - q$ and q is the number of constraints on the initial and final conditions, and the terminal time T is assumed to be unknown for the minimum time problem.

The initial and final conditions on the variables of Eqn (18) are typically given by: $x(0) = 0, x(T) = D; v(0) = 0, v(T) = 0; f(0) = 0, f(T) = 0$. The subject starts and stops a movement of distance D with zero velocity and force. This is the paradigm frequently used in experimental studies. Under these conditions from Eqn (19), $N = 2$, i.e., there will be two switchings in the control signal. The movement is initiated by the activation of the agonist, switching to antagonist, and finally agonist again, which leads to the triphasic response pattern seen in many studies.

In the Fitts-Peterson experiments, if the coefficient of friction between the target plate and the stylus is large such that sliding does not occur, there would be no requirements on values of terminal velocity and force. From Eqn (19) ($q = 4, m = 2$) the number of switchings N will be zero. This would be the case when the movement is stopped against a mechanical barrier that the subject is told to strike in minimum time. In Fitts' experiments, the subject did not attempt to minimize the time to reach the target in a single movement. The movements were reciprocal between two target plates. For example, suppose the subject had just reached the right target plate in the minimum possible time, then to return to the left target plate he would have to reverse the direction of the force. He could return to the other target in less time if he allowed the final force to be less than it would be if he had minimized the previous movement time. Thus, the average time for movement would be minimized the previous movement time. Thus the average time for movement would be minimized for a periodic movement for which $x(0) = 0, x(T) = D; v(0) = 0, v(T) = 0;$ and $f(0) = -f(T)$. From Eqn (19) ($q = 5, m = 1$), this set of conditions yields one switching time. The solution of Eqn (19) and the analysis of minimum time depends on the boundary conditions and the number of switching times.

10. DUAL STRATEGY HYPOTHESIS

Gottlieb et al[36,40] have proposed a dual strategy hypothesis. This theory attempts to reconcile many apparent conflicts in the motor control literature cited above and to explain how accurate, single-joint human movements are controlled. The theory embraces

movements of different distances, with different inertial loads, to targets of different widths over a wide range of experimentally manipulated velocities. The theory is predicated on three propositions: (i) the movements are plannned according to 'strategies' of which there are at least two: a speed-insensitive strategy and a speed-sensitive strategy, (ii) these strategies can be equated to sets of rules sufficient to perform diverse movement tasks; the choice between these two strategies is contingent upon whether movement speed and/or movement time (and hence appropriate muscle forces) must be constrained to meet task requirements, and (iii) the EMG can be interpreted as a low-pass filtered version of the controlling signal to motoneuron pools. This controlling signal can be modelled as a rectangular excitation pulse in which modulation occurs in either pulse amplitute or pulse width. Movements different distances and loads are controlled by a speed-insensitive strategy which modulates pulse width. Movements in which speed must be explicity regulated are controlled by a speed-sensitive strategy which modulates pulse amplitude.

Figure 3 illustrates some of the steps between the definition of the task and the performance of the movement. The control input is the neural input to the alpha motoneuron pool, which is defined as the excitation pulse. It represents the net descending presynaptic input, excitatory and inhibitory, which converges and summates within the alpha motoneuron pool. The rules of a strategy allow the motor control system to generate a movement-specific excitation pulse. The output of the motoneuron pool is a composite train of action potentials at different frequencies in a variable number of neurons. The response of the muscle has two physically distinct and separate processes which produce different measurable quantities: EMG and tension. Correlations between electrical and mechanical responses are a consequence of their shared causal stimulus, not because of any direct cause-and-effect relationship between them.

11. PREDICTIONS FROM TWO STRATEGIES

A *speed-sensitive strategy* is used when the subject exerts control over the speed at which the movement must be performed or over movement time. The excitation pulse intensity is modulated. The duration may change in the same or the opposite direction as intensity or may remain constant. The initial rate of
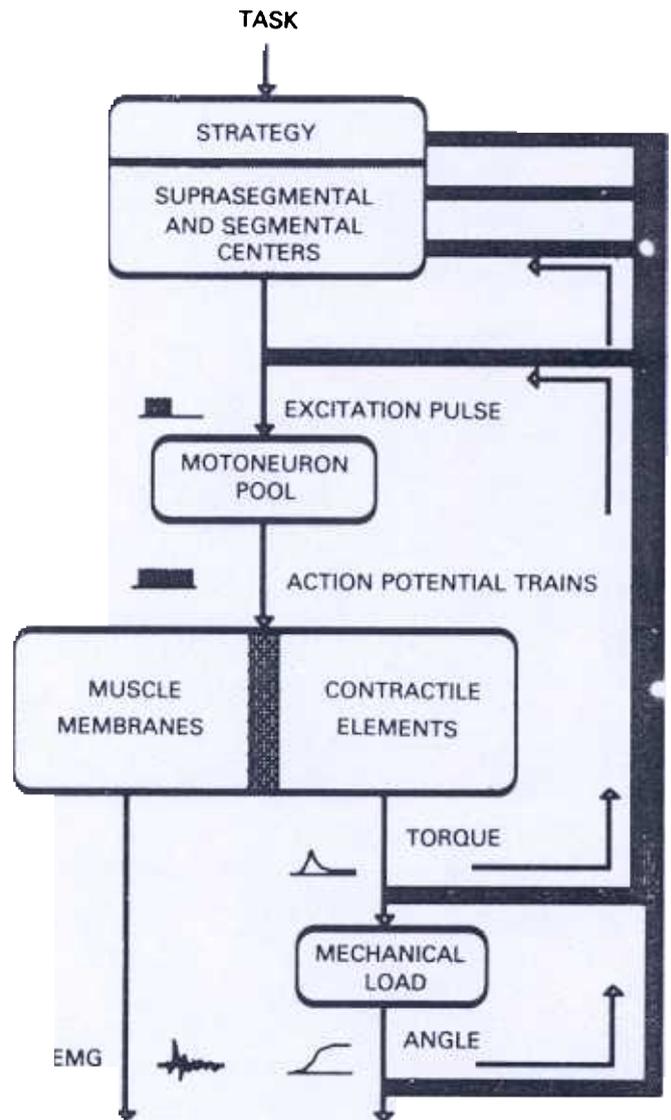

Figure 3. A diagram illustrating selected portions of the motor control system.

recruitment and firing rates of the alpha motoneurons are adjusted to adapt to changes in the task. This results in changes in the initial slope of the EMG and in the area of the agonist burst. The duration of the agonist burst will be nearly constant if the duration of the excitation pulse is constant. The slope of the initial rise in muscle force (or joint torque) will scale with the intensity of the excitation pulse. For constant inertial loads, this implies that acceleration will be proportional to intensity. This strategy is used by subjects who are given one of at least four kinds of task constraints: (i) movements with controlled variable duration, (ii) movements with controlled constant duration, (iii) movements of controlled speed, and (iv) movements of controlled accuracy.

Speed-insensitive strategy is used when the subject does not exert explicit control over speed at which the movement is performed. The excitation pulse intensity is constant and the duration is modulated. The initial pattern of motoneuron pool discharge is independent of the magnitude of the task variable. This generates EMGs which rise at the same rate, irrespective of changes in distance or load. Changes in the task affect the area and duration of the EMG burst. Because initial motoneuron pool activation is insensitive to the magnitude of the task variable, the initial muscle force is also unaffected. For constant inertial loads, this is reflected in constant initial rates of acceleration. For different inertial loads, acceleration scales inversely with load. This strategy is used to quickly move different distances or loads in the absence of additional constraints on movement speed or time or changes in absolute accuracy requirements.

The experimental evidence for these two strategies has been presented in several publications[36,40,42-44]. By organising the experiments according to these two strategies, we have been able to resolve many of the apparent conflicts over whether measures are proportional to some experimentally manipulated parameter or are invariant.

The major contractile event which determines movement termination is associated with the antagonist burst. We believe it can be described by the same rules used for the agoinst burst but needs one additional rule for its latency. Latency appears in large part to depend upon the duration of the movement, although the relation is not one of simple proportionality. EMG data for the speed-insensitive strategy show the latency of the antagonist EMG burst to be proportional to distance or load. This delays the application of decelerating forces when the movement time is prolonged. A similar conclusion may be drawn from the speed- sensitive strategy experiments.

Many investigators have argued or assumed that movements of the type discussed here are controlled by a 'triphasic pattern' consisting of an agonist burst, an antagonist burst and a second agonist burst, occurring in that temporal sequence. The triphasic bursts are not an invariant feature of this class of movements. The second agonist burst usually wanes and eventually vanishes with decreasing movement speeds, but the same may be said for both of the other two bursts, albeit at lower speeds. Unlike the other two bursts, the second agonist burst is

far more task and subject specific as to whether it will be present at all. In some tasks and some subjects it is almost always present, while others rarely demonstrate it. We suspect that with practice and training, anyone can generate it, presumably by learning to go faster and thus changing the dynamics of the movement.

12. MULTI-JOINT MOVEMENTS

The discussion in the foregoing sections was limited to single joint movements. Nearly all activities of daily living involve multijoint movements in a three dimensional space. Information concerning control of such movements is very limited in spite of the fact that human gait has been studied for a long time. The reaching movements studied by Fitts[16] involved multijoints. How do we organise and control such movements? In which space(s) or coordinate(s) systems does the brain represent movements, that is, is the movement represented in terms of muscle lengths, joint angles, limb motions, or in some other terms? Hollerbach[45] has proposed 'a three-level hierarchical movement plan which converts a movement command to muscle activations by first planning the movement at the object level, then translating the object trajectory into coordinated joint movement, and finally converting from joint movement to muscle activations'. This proposal is essentially based on the common practice in robotics. However, Hogan[46] has argued against this hypothesis for two reasons: 'First, when simple movements are described in joint space, there is a pronounced lack of pattern or regularity. In contrast, a reasonably regular pattern emerges when the same movements are described in terms of hand motion. Second, the most detailed joint-based strategy proposed to date fails to account for common observations of joint motion reversals during simple movements'.

Hogan[46] has proposed that the movements are planned in terms of the hand motion in external space and that the trajectories are based on the principle of minimum jerk. As Hogan has noted, the hand motion does not uniquely specify the joint motions. There are redundant degrees-of-freedom and somehow the central nervous system deals with these extra degrees. For a single joint, a movement from one point to another based on minimum jerk criterion would have a symmetrical velocity profile. The experimental observations do not support this.

Based on simulation studies, Hogan[46] has proposed that 'simple movements are (i), planned in terms of hand motion in external space, (ii) expressed in terms of a virtual trajectory, and (iii) executed via the mechanics of the neuromuscular system, which acts to keep the actual path of the limb reasonably close to the virtual trajectory, but not identical to it.

At present, the analysis of multijoint movements is mostly limited to kinematics. Although in human gait studies EMGs have been recorded, the calculation of forces involved from the EMGs has been a difficult problem[39].

13. HIGHER MOTOR CONTROL

Since the pioneering work of Evarts[47] in recording activity from pyramidal tracks in unanesthetized monkeys, considerable effort has been devoted to correlate activities from higher centre neurons to muscle activities and movements. Murphy _. _al[48] recorded the activity of cells in the motor cortex during forward reaching by monkeys. No simple relation was observed between the single cell activity and the EMG, even when the muscles from which the EMG was recorded were activated by the microstimulation. Murphy concluded that 'the production of any movement, however complex or discrete it may seem peripherally, engages a complex population of precentral neurons, such that any one neuron may behave similarly for overtly different movements[48]. This would imply coding of the movement trajectory at the motor cortex level in the neuronal population rather than a single neuron. Not surprisingly, extensive studies on single neuronal recording have provided very little information concerning the organization of movements. Studies by Georgopoulos[49] indicate that single cells do not provide unambiguous information about the direction of the movement and for a particular movement direction, a whole population of cells will be engaged.

An important task for neurophysiology and other disciplines, such as engineering, psychology, kinesiology, etc, is to elucidate the intervening steps and coordinate transformations of target location in space to body-based coordinate system and ultimately to various muscle activities. This task is made even more challenging because of the fact that we have very limited access to intermediate systems and signals and must rely on integrating information from animal studies and limited information from human studies.

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