

CONTROL OF FAST GOAL-DIRECTED ARM MOVEMENTS

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Abstract

Fast goal-directed arm movements in the form of simple movements or parts of more complex movements, were studied. The position, velocity and acceleration of the wrist and EMG activities of biceps and triceps were continuously recorded during the movements. It was found that for movements of the lower arm:

a) The main pattern of EMG activity in the agonist consists of an initial burst of activity, followed by a period of depressed activity, followed by a second burst of activity. The antagonist muscles are active during the depressed period of the agonist activity.

b) The duration of the initial burst of agonist activity increases with the distance over which the wrist has to move. In general, the intensity of the activity does not change.

c) When, without the subject's prior knowledge, a movement is mechanically blocked, the pattern of EMG activity over at least the first 100 ms is the same as that for the case of an undisturbed movement. This suggests that muscle activation patterns are preset over this period and are not immediately modified by proprioceptive information.

Experiments were also carried out in which either the overall movement rate was changed or the inertial load of the arm system was artificially changed. From these experiments it was concluded that depending on load and desired overall rate, a kind of muscle activation level or muscle tone is first chosen. Muscle activation patterns are next constructed. The muscle activation level is taken into account in constructing these action patterns.

INTRODUCTION

Fast goal-directed arm movements are executed either as discrete movements e.g. grasping and indicating, or as a part of more complex motor tasks e.g. playing a musical instrument. These movements were chosen as an object of study of motor control because they are very common and because

arm movements are well accessible for measurement with respect to displacement, force and EMG activity.

The methods used to describe movement patterns and cybernetical actions vary from one author to another depending on their aims and disciplines. Examples range from the information capacity function (Fitts & Peterson, 1964) to a description in the

Fourier domain (Hatze, 1976). In this study an attempt is made to describe movements in terms of EMG patterns since these represent the activity of the nervous system upon the muscle. Much work has already been done to correlate this signal to muscle force, but unfortunately views differ as to how a quantitative interpretation can be made (Bigland & Lippold, 1954; Milner-Brown & Stein, 1975). Also very little is known about the EMG during ballistic movements shorter than 200 ms duration.

In this paper special attention is paid to fast arm movements (as in, for example, grasping) consisting of elbow extensions. Such movements have the advantage that the recording is simplified and the number of muscles involved is relatively small. However, it will be shown that the results obtained appear to hold for many other movements as well.

Once the structure of the action-patterns is analysed, it seems of interest to investigate what happens when the movement is externally disturbed. The way in which proprioception is used for movement control may thus be revealed. Two types of interference will be described: changes of inertial load and mechanical blocking of the movement. It will be seen that a kind of 'action program' is used for controlling a fast goal-directed movement. Such a program holds for a certain period and consists of a set of instructions as to which muscles to choose, their activation intensity, and the duration of the programmed activities. Although proprioceptive information undoubtedly plays a role in constructing the action programs it is not used for direct control of muscle activity during these movements. It has already been shown that in the case of hand-writing and other fast movements, programs of the kind mentioned above are very likely to be used. (Denier van der Gon & Thuring, 1965; Denier van der Gon & Wieneke, 1969; Bizzi, Kalil & Tagliasco, 1971; Dijkstra & Denier van der Gon, 1973; Brooks, 1974).

MATERIALS AND METHODS

Two movement recording systems were used. The first one consisted of a chain running over two sprockets set 1.5 m apart. The subject's wrist was held in a cuff attached to the chain so that movement was more or less restricted to a straight line in the horizontal plane at shoulder height (Fig. 1). The subject was held in a harness to ensure that the movement was produced only by the shoulder and elbow joints. Unless otherwise specified, position recordings are given along the track of the wrist. A potentiometer attached to one of the sprockets gave the position signal. Its first and second derivatives, obtained using the method of cubic splines (Reinsch, 1967, 1971) gave the velocity and acceleration of the movement of the wrist.

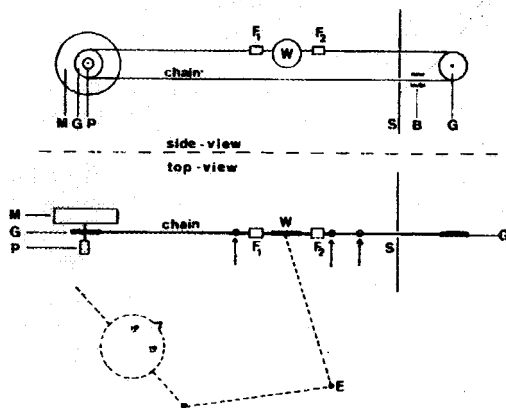


Figure 1
Schematic top-view and side-view of the 'chain' recording system:

W—universally joint wrist-cuff, E—elbow, $F_{1,2}$ —force-transducers, M—electric motor, B—bolt, G—sprocket, P—potentiometer, S—screen to prevent subject seeing the bolt.

The starting point of the movement (●) and the position of goals (○) were displayed on the frame of the apparatus just under the chain.

The effective inertia of the arm could be increased or decreased by means of a feed-

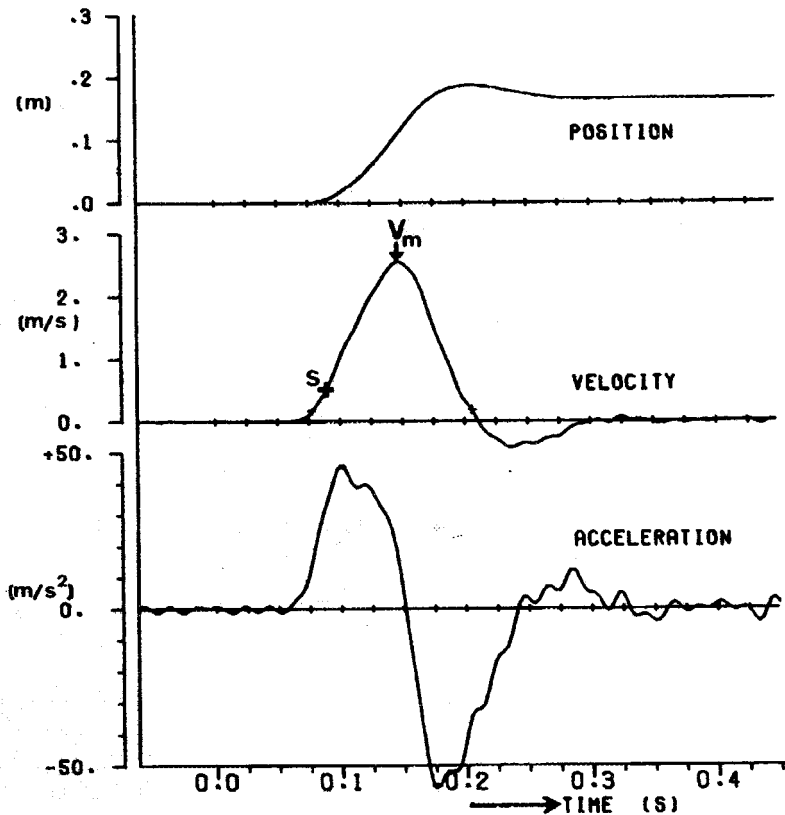


Figure 2

Typical example of records for a 15 cm movement of the wrist on the chain-system:

S—synchronisation point of time for ensemble averaging,

V_m —maximum velocity.

back mechanism. Two identical piezo-electric force transducers on both sides of the cuff (Fig. 2) measured the force exerted on the wrist. An electric motor mounted on one of the sprockets was controlled by the force and acceleration signals. The chain could also be mechanically blocked with a bolt. The blocking system was so constructed that it was inaudible to the subject and could not be seen by him. He thus had no knowledge before he began to perform the movement that it would be blocked.

Seven healthy male right-handed subjects participated in these experiments. They

were instructed to move their hand from a fixed start position to a prescribed goal. They were allowed to form a visual central representation first. They were free to start the movement when they liked, but it had to be carried out at maximum speed. At least 20 secs elapsed between each movement. During this time the subject had to return his wrist to the start position. Each goal was randomly selected from a choice of four, representing movements of 7.5, 15, 22.5 and 30 cm. Before an experimental session twenty trials were made in order to allow the subject to become accustomed to the appar-

atus. In experiments in which the inertia was changed, the subject was again allowed to make twenty trials before the actual recording started.

The other recording apparatus used was a 'Selspot' system, commercially available. It consists of a dual axis lateral photodetector in front of which a lens (Canon 50 mm, 1:0.95) is placed. With the help of this system infrared Light-Emitting-Diodes (LEDs) may be detected (for a review see Woltring, 1975). The LED's weighed less than 2 g and are connected to very thin flexible wires. The advantage of the Selspot system is that by fixing the LEDs to limbs or fingers, virtually undisturbed movements may be recorded in a simple way under normal illumination. Since only one camera was available, the movements had to be restricted to one plane perpendicular to the camera axis. Position data (x-y coordinates, accuracy 0.5% full scale) were sampled at 320 Hz and fed into a HP21MX computer for further analysis.

First of all, movements were made with this system using the same set up and instructions to the subject as in the experiments in which the chain system was used,

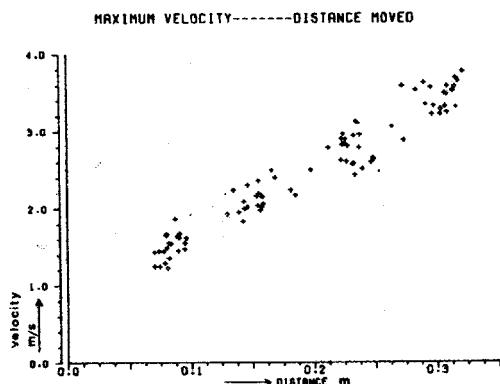


Figure 3
Maximum velocity versus distance moved in 84 trials for one subject. It is seen that in the range from 6-32 cm V^m increases linearly with distance (corr. coeff. $r = 0.97$).

but the wrist of the subject was not connected to the chain. In this way it could be checked that the chain did not influence significantly the movement patterns. Next, it was used to record a number of comparable movements which demand special skills. A professional violinist (over 40 years of experience), a part-time professional trombone player and a professional paintress participated in these experiments. In violin playing the position changes of the pitch-finger (i.e. left middle finger) on the finger-board were recorded while a tune was played. LED's were fixed on the finger, the wrist, elbow and shoulder-joint. Virtually the same set up was used to record the movements of the trombonist's wrist in moving the slide. The paintress was asked to draw a part of a human face. The paper was placed over a sheet of glass and very small LED's were mounted on the pencil. The camera recorded from a distance of 50 cm through the paper.

Finally, eye movement recordings were made using the instrumentation developed by Collewyn, van der Mark & Jansen (1975). A small induction coil is fixed to the eye. Eye position (angle of rotation) with respect to the direction of an alternating magnetic field is measured by recording the induced e.m.f. The subject was instructed to change his direction of view from one object to another in one sweep. The objects were black dots on a screen about 3 m in front of the subject. Two subjects participated in these experiments.

Electromyograms (EMGs) were recorded synchronously with the position data using bipolar silver surface electrodes with a diameter of 0.5 cm. They were placed transversally, 2.5 cm apart, on the muscle bellies where the threshold-current for electrical stimulation had a minimum value. The EMG-signals were rectified and slightly smoothed ('time constant' 10 ms) (Strackee, 1961; Gottlieb & Agarwal, 1970). As a rule the EMGs of biceps (caput longum) and

triceps (caput laterale) were recorded (Bas-majian & Latif, 1957; Barnett & Harding, 1955; Travill, 1962). It was confirmed that other flexors acting on the same joint (brachialis and brachioradialis) behaved roughly in the same way as the biceps.

Even if the movement is accurately reproduced, the EMG activity varies considerably from trial to trial. To reduce this variability ensemble averages of the EMG-time signals are calculated. The moment at which the velocity of the wrist reaches the value of 0.5 m/s is taken as synchronisation for averaging. At least up to this moment the velocity signals for all distances are almost equal (Fig. 4). In the blocked movements the moment at which the recorded force reaches 20 N is used for synchronisation. The figures were 'normal' and 'blocked' EMG-patterns are compared, are so arranged that the first flanks in the averaged agonist activity coincide. Zero-point on the time axis is arbitrarily chosen. EMG amplitudes were compared only in those cases where the electrode placing was not altered or disturbed.

RESULTS

1. First of all, movements recorded on the chain system, were compared to movements recorded with the Selspot system. Velocity and acceleration patterns and EMG activities did not noticeably differ when movements over the same distance and direction were recorded by the two systems.

In Fig. 2 a typical recording of position, velocity and acceleration along the wrist track is given for a 15 cm extension movement in which the chain-recording system was used. The mechanical characteristics such as maximum speed, duration etc. appeared to be quite reproducible for one subject, but slight differences between subjects were seen. The values are in good agreement with those found by others (Terzuolo, Soechting & Viviani, 1973; Brooks, 1974; Brown & Slater-Hammel, 1949).

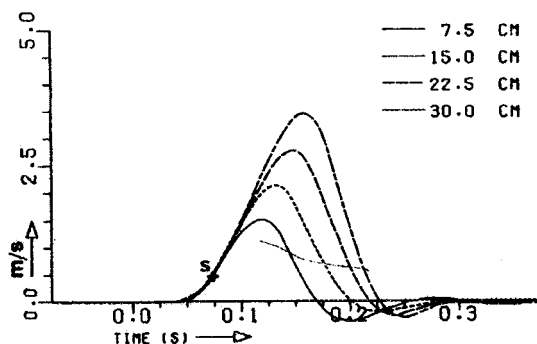


Figure 4

Averaged velocity signals for four movements of different length (7.5-30 cm), average of 20 trials each. It is seen that the initial velocity patterns are almost equal, at least up to the synchronisation level used (S-0.5 m/s).

Movements with overshoot as well as undershoot appeared randomly in all series. No attempt to categorise or to treat them separately has been made. For movements of different length it was found for all subjects that the maximum velocity (defined as V_m in Fig. 2) varied almost linearly with the distance moved (Fig. 3). The averaged velocity patterns (Fig. 4) of four movements of different length (7.5-30 cm) show that these movements all start in roughly the same way. When a larger distance has to be covered a longer movement time is necessary.

An example of the EMG pattern is given in Fig. 5. It shows clearly the three burst pattern in the signals obtained from biceps and triceps. The time axis is the same as for Fig. 2. Two bursts of activity can be seen in the agonist (T_2 , T_2 and T_3 , T_4) separated by a period of depressed activity (T_2 , T_3) during which the antagonist is active (T_5 , T_6). The first agonist burst will accelerate the arm, the antagonist burst will retard it. The possible role of the third burst will be considered in the discussion. A similar pattern can be observed in flexion movements.

Unfortunately not all EMG-recordings

are as pronounced as the one shown in Fig. 5, so that ensemble averages have been used. EMG-recordings of triceps (Fig. 6) and biceps (Fig. 7) during the movements given in Fig. 4 yield a clear change in pattern when the distance moved increases. The first burst of activity in the agonist becomes longer (60-120 ms) but the average intensity is about the same. The activity of the antagonist seems to be of about equal duration (± 90 ms) and intensity for all distances. The period of

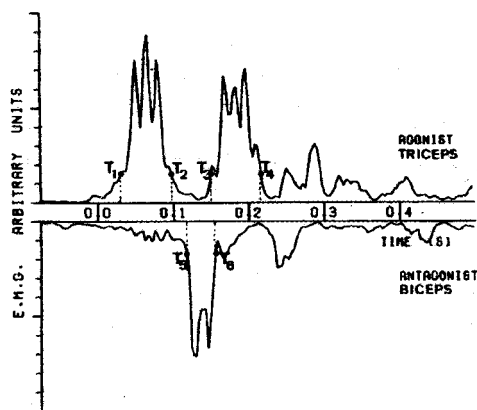


Figure 5

EMG pattern of the triceps (agonist) and biceps (antagonist) during the extension movement shown in Fig. 2. EMG signals are rectified and filtered. $T_1 \dots T_6$ are used to quantify the EMGs. T_1 and T_2 represent the onset and cessation of the first burst of activity in the agonist, T_3 and T_4 the second burst and T_5 and T_6 the onset and cessation of the burst of activity of antagonist. For further explanation see text.

depressed activity between the two agonist bursts also has about equal duration for all distances. The antagonist burst and the period of depressed agonist activity are thus always coincident. The EMG-amplitude during the second period of agonist activity is less reproducible from one trial to another. The muscle activity extinguishes gradually when the movement is terminated.

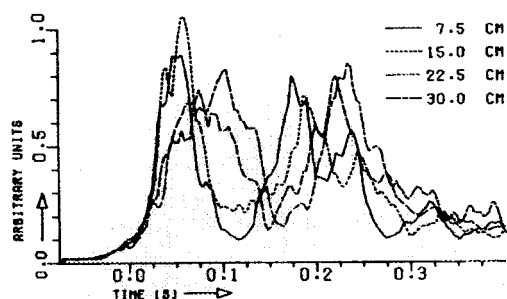


Figure 6

Averaged EMG patterns (20 trials each) of extension movements of four different lengths recorded from the triceps. Velocity patterns are given in Fig. 4.

To characterize the EMG pattern in a more quantitative way T_1 to T_6 as indicated in Fig. 5 were determined by choosing a level of 12% of the highest recorded EMG-activity of the muscle in question out of the 40 myograms recorded with the same undisturbed electrode position. Ten movements to the same goal yielded a standard deviation of 5 ms for T_1 , T_5 and T_6 . The standard deviation for T_2 , T_3 and T_4 was 20 ms. The relationships of the six points of time to the distance covered are summarized by the regression lines in Fig. 8. Each one represents the least square fit to 40 measurements

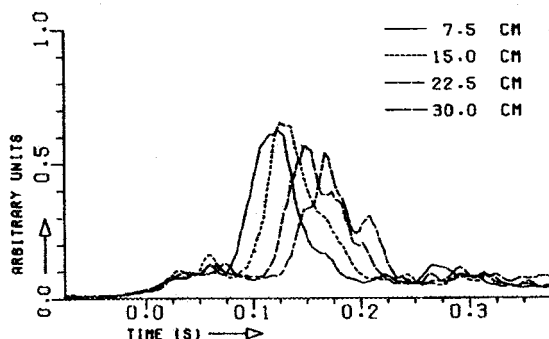


Figure 7

Averaged EMG patterns of the same movements as in Fig. 6, recorded from the biceps.

on a subject. It is seen that the moment T_1 does not change with distance. Thus the synchronisation procedure is justified. For larger distances of movement the first burst of activity is prolonged (T_1 , T_2). The other moments in time (i.e. T_3 to T_6) seem to vary in the same manner. In an additional set of experiments it was confirmed that the sequence of the movements of different lengths had no influence on the results.

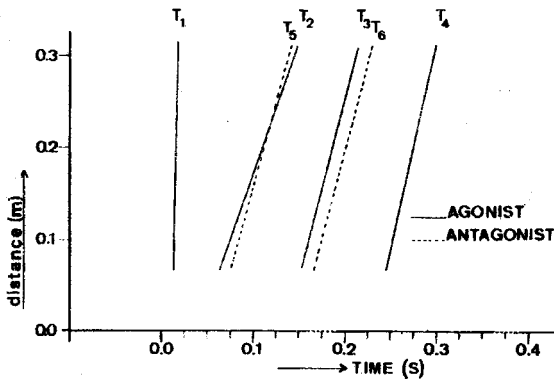


Figure 8
Variations of the times at which the various EMG thresholds (as shown in Fig. 5) are reached for movements of different distances. Each regression line presented is a least square fit to 40 trials.

It was concluded that, for fast goal-directed extension movements, the muscles are activated in a reproducible way. Movements of different length are caused by a change of the activation duration of the agonist, leaving intensities (EMG amplitudes) almost the same.

2. To investigate in what way movement feedback information contributes to the patterns of EMG-activity described above, recordings were made when movements were completely mechanically blocked. The same type of movements as in 1 was carried out but one in five were randomly blocked with the bolt (Fig. 1) without the subject's prior knowledge. (It should be realized that

the subject now knew that his wrist *might* be blocked.) Neither mechanical data nor EMG-recordings of the undisturbed movements in this series showed any difference from those recorded in 1. When blocked movement EMGs are compared with those of a free movement of 7.5 cm (Fig. 9) very little difference can be detected during approximately the first 100 ms. The first burst of the agonist EMG is present in both cases and the antagonist activity is also seen but of slightly less duration than for a free movement, in spite of the fact that, in this case, a retarding force is superfluous. The first 100 ms of the EMG pattern does not seem to depend on the performance but only on the goal the subject is aiming at. After this period the antagonist is suppressed in comparison with the EMG of an undisturbed movement. For an intended movement of 15 cm a suppression after approximately 100 ms is also seen (Fig. 10). For an intended movement of 30 cm almost no antagonist activity is seen. This is to be expected since in a free movement this would only appear after 100 ms (Fig. 8).

The average force responses for the blocked movements (Fig. 11) can be considered to represent the net muscle forces acting on the lower arm. It is seen that the four forces build up almost equally and that after 40 ms they reach a maximum. This is in agreement with the observation (1) that movements covering different distances are carried out with equal intensities but different durations.

It is concluded that for at least the first 100 ms the motor system does not make use of proprioceptive movement information for control.

3. After the 'preprogrammed' period of 100 ms (see 2) significant changes are seen when blocked movement activities are compared to those of a free movement. To investigate the role of information arising from the wrist region where contact was made with the cuff, the experiments were repeated with

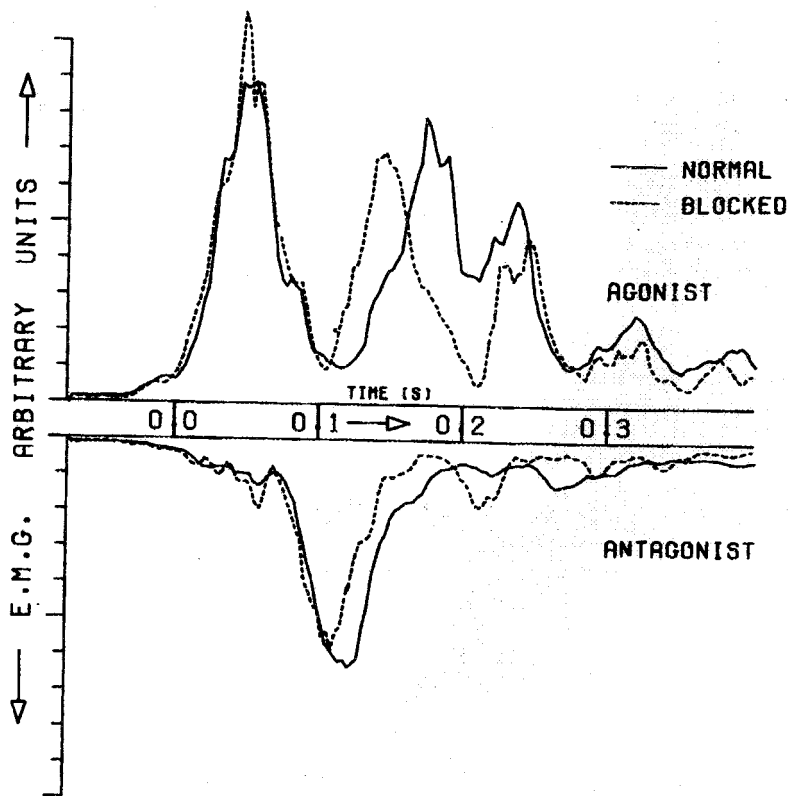


Figure 9

Averaged EMG (20 trials) of triceps (top) and biceps (bottom) during a movement of 7.5 cm (continuous line). An averaged EMG (6 trials) is shown (dotted line) using the same electrode-setting. The subject aimed at the same goal but the movement was unexpectedly completely blocked. It is seen that the EMG patterns coincide during the initial 100 ms at least.

one of the subjects but this time a pressure cuff was applied around the lower arm 15 cm from the elbow joint and the wrist region was anaesthetized with 25 ml procaine 1%. When tested to the depth of the bones, all sensations of pain, pressure and touch were abolished over a region of 4 cm on both sides of the wrist-cuff. Nevertheless, the same EMG, force, and velocity-patterns were found in this situation. This makes it very unlikely that sensory information from the

wrist region plays a role in the observed phenomena.

4. From the experiments described in 1 and 2 above it followed that in the case of fast movements, the muscle activity is centrally preset over a period of at least 100 ms. The question now arises as to how the central nervous system takes variations in the inertial load into account. In such cases the intensity and/or the duration of EMG activ-

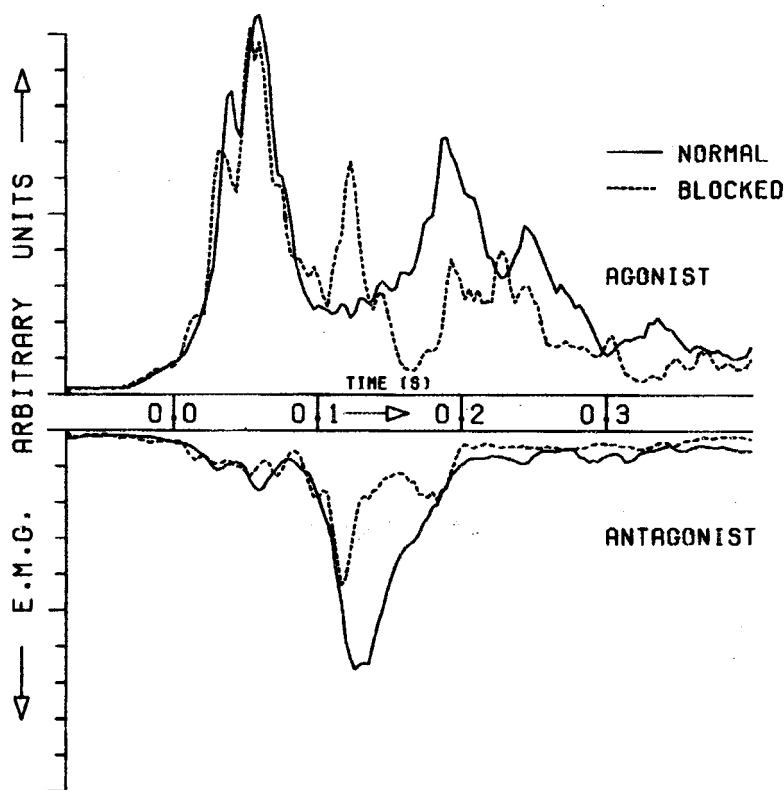


Figure 10

EMG signals as in Fig. 9 but for an actual movement and an intended but blocked movement of 15 cm. Again the EMG activities shown in both records are initially coincident.

ity would have to be changed. To investigate this the inertia of the arm was artificially *increased* by 50% in a first set of measurements and *decreased* by 20% in a next set. After a few trials the subject easily adapted to the new situation. From accelerations during free movements, forces in the wrist during blocked movements and EMG patterns in both types of movement, it could be concluded that the intensity of the activations was always the same but the durations altered. A change in the time of onset of antagonist activity (T_5) and in the duration of the first burst of agonist activity was observed. The duration of the second burst

and the depressed period of activity in the agonist were also extended. The timing of the antagonist activity (T_5 , T_6) for three values of the inertial load is summarized in Fig. 12. The phenomena observed in position recordings and the derivatives correspond with what is to be expected from a constant activation level over different durations: the initial acceleration varied inversely with the inertia.

5. In the foregoing it was shown that the movements always start in the same way irrespective of the distance to be covered. As is to be expected, larger movements have

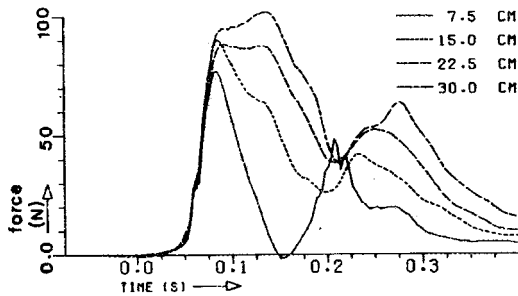


Figure 11

Averaged forces exerted by the wrist when movements aimed at different goals are blocked. EMG records for the movements of 7.5 and 15 cm are given in Fig. 9 and Fig. 10. The forces develop in the same way, independent of the distance aimed. For further explanation see text.

longer duration. The results from the goal-directed movements described above in sections 1-4 are now compared with other forms of goal-directed movement:

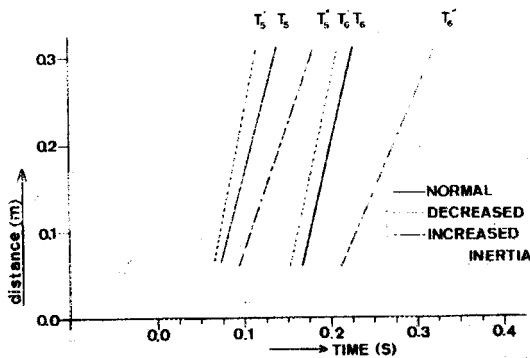


Figure 12

Comparison of antagonist EMG-activity for movements during decreased (80%) (T_6 , T_8), normal (100%) (T_5 , T_8) and increased (150%) (T_5 , T_8) inertial loads, 40 movements each. The regression lines presented are least square fits to 40 points each. It is seen that the movement control pattern adapts to changes in inertial load by adjusting the timing of the antagonist activity.

Eye-movements

An eye movement is an obvious example of an accurate goal-directed movement but there are many differences between the eye movement system and the arm movement system. Even the physiological properties of the muscles involved are rather different (Cook & Stark, 1967). Nevertheless a comparison between the movement patterns

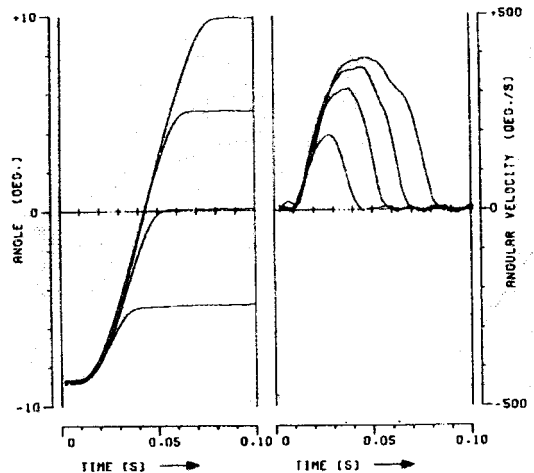


Figure 13

Angular displacement and angular velocity of the right eyeball when the subject had to change his direction of view in one sweep over the angle from 5°-20° (see text).

seems worthwhile. When a subject is asked to change his direction of view over different angles, the initial velocities are the same (Fig. 13) meaning that equal initial force is used. The duration depends on the angle to be rotated. Arm movements take twice as much time as eye movements, but it seems that the same type of movement control mechanism is used.

Violin and trombone playing

When a prescribed tune is played on a violin the finger position changes on the finger board are well-defined, albeit, not visually. A tune consisting of notes of equal duration was played at a prescribed rate, using only one string and the middle finger. A sample

set of velocity recordings of position changes over different distances is shown in Fig. 14. Certainly more muscles and more joints are involved in these complicated movements but the same movement control mechanism is obvious. The initial velocity is the same and independent of the distance to be covered, but the duration of the movement changes accordingly.

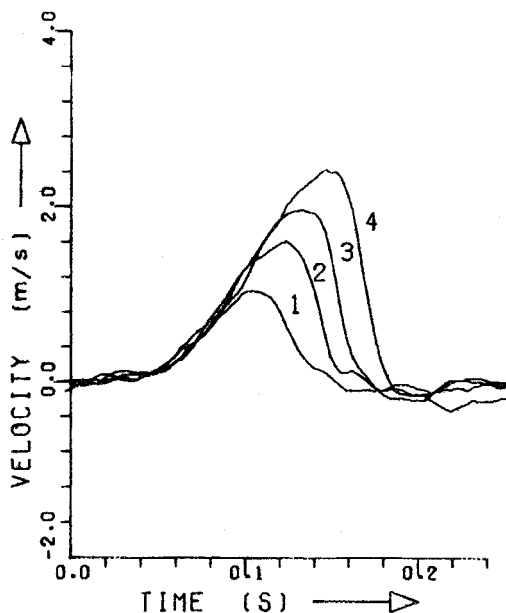


Figure 14

Velocities along the finger-board in violin-playing. The violinist was instructed to play a tune using only one string and one finger. The records correspond to distances of 5.5, 9.5, 12.3 and 16.5 cm (1 to 4). The velocity-time-distance pattern is rather similar to the one for fast extension movements (Fig. 4).

When the trombone is played, the pitch is attained by moving the slide into the desired position. This movement is performed mainly by the elbow, the wrist moving more or less along a straight line, rather similar to the movements analysed in 1 above. Velocity recordings (Fig. 15) of the wrist along its

track all start in a similar way and again a larger distance requires a longer time. The EMG-signals of agonists and antagonists were also found to exhibit similar patterns as those in sections 1 to 4.

Pencil drawing

One might form the conclusion that the mode of control described above is universal for all movements. However, a number of examples in the literature shows that this is not the case. A different control mode is illustrated in Fig. 16. When the movements made during shading are analysed, it is found that all strokes take about the same time irrespective of their length. Strokes of different lengths are clearly caused by different activity levels.

Obviously movement intensity decreases if movements are more slowly carried out. It is interesting to note that if a violinist is

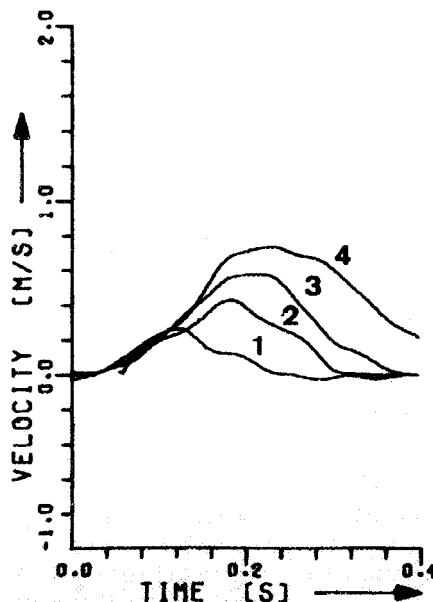


Figure 15

Velocities of the trombone slide. The records correspond to distances of 3, 6, 10, 17 cm (1 to 4).

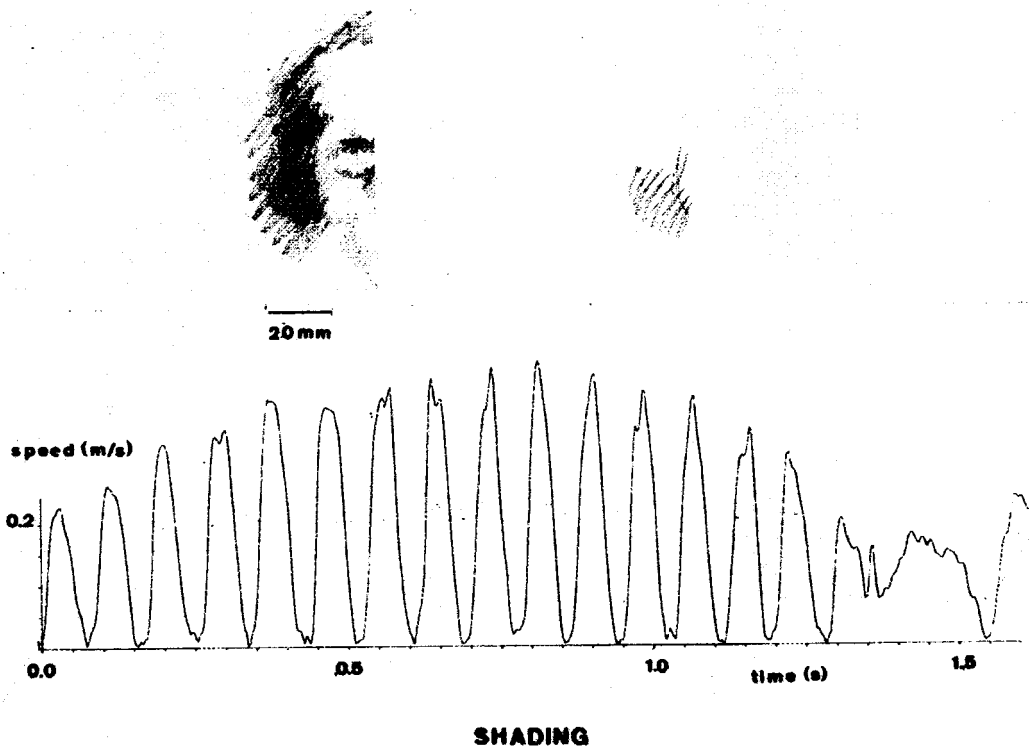


Figure 16

Velocity along the track of the tip of the pencil when part of a drawing was shaded in (inset left: the actual picture, inset right: the part of the movement which is analysed). It is seen that shading is a very rhythmic movement in which different distances are covered in equal times.

asked to play the same tune at a lower rate, his movements become slower (Fig. 17) suggesting a lower level of overall activity.

DISCUSSION

In the foregoing it was seen that many fast goal-directed movements show the same basic pattern of movement control. A change of magnitude of these movements resulted from a change in activation duration while the intensity of activation was not changed. The same basic pattern of movement was found by Denier van der Gon and Thuring (1965) when studying movement strokes of different sizes in a handwritten

word. In spite of the anatomical differences involved in the given examples the same kind of basic control seems to be used for executing these fast goal-directed movements. The control mode described here is not the only one the central nervous system has at its disposal. In shading it was shown that different shading strokes may take the same time, irrespective of their length (Fig. 16). Different magnitudes result from different intensities (for other examples on drawing movement studies see Denier van der Gon, 1979.) The latter type of control is found also in the vibrato of violinists (Schlapp, 1973) and trombonists. Further, when the same word has to be written in

different sizes, the muscle timing pattern remains the same, indicating that the overall size of the word is determined by the intensity level of muscle activations (Denier van der Gon & Thuring, 1965). It seems that the instruction given to the subject is very important for the choice of the control-mode (Brown & Slater-Hammel, 1949). Different forces seem to be used to realize overall effects (shade, vibrato, word-size, general tempo) while an adjustable timing is used for attaining a well defined end-point.

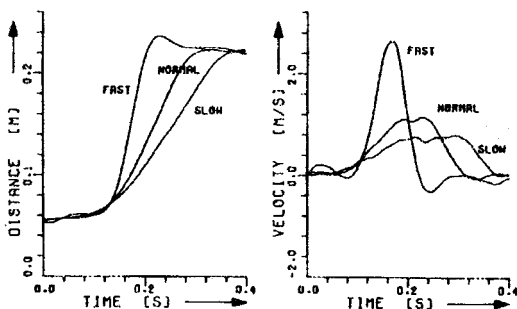


Figure 17

A comparison of the same position change and corresponding velocity, of the violinist's pitch-finger when a piece of music is played at three different overall tempos (slow, normal, fast, in the ratio: $\frac{1}{2}$, 1, 2). It is seen that initial velocities clearly differ.

The control mechanisms can be further analysed with EMGs. The technique of ensemble-averaging, as described in this paper, proved to be a useful tool to reveal the time properties of the EMG signal once a good synchronisation point has been chosen. Since the research of Wachholder & Altenburger (1926) a three burst pattern in the EMGs of agonist and antagonist during fast ballistic arm movements has been reported (Agarwal & Gottlieb, 1972; Angel, 1974; Hallett, Shahani & Young, 1975). The EMG patterns shown in Figs. 6 and 7 are in agreement with this. They confirm the relation between activation time and distance

covered which is to be expected from the movement recordings. The parameter of paramount importance appears to be the time elapsed between the onset of the first agonist EMG-burst and the antagonist EMG-burst. Further, the interpretation would be that neuronal activity (instantaneous spike density) of the innervating muscle efferents during the period a muscle is activated, does not depend on the distance to be covered because: 1) no marked systematic differences in the EMG amplitudes are seen (Figs. 6 and 7); 2) the initial velocities are equal (Fig. 4); and 3) when the movement is blocked, forces build up equally and reach about the same maximum values (Fig. 11).

The antagonist burst of activity is not triggered by the movement itself as it is also present when the movement is blocked. Also the period of depressed activity in the agonist appears at its usual time, indicating that it might well be under central nervous control. During the first 100 ms of a fast movement no proprioceptive information appears to be used, suggesting a kind of preprogramming of the muscle activations. This conclusion is in agreement with the results obtained from experiments on unexpected loading and unloading of arm movements (Angel, 1974; 1975).

After the initial '100 ms period' deviations from the normal patterns are seen when the movement is blocked. These deviations are not induced by sensory receptors in the wrist region as could be concluded from the experiments described in section 3.

Much has been argued about the role of the third burst of activity in the EMG pattern. To accelerate and decelerate a mass two bursts would suffice. However, in a preprogrammed or open loop system the demands on accuracy for these bursts to stop the movement properly would be extremely high. A centrally planned third activation might be of advantage. This third burst compensates partly for the antagonist rest force, bringing the movement more rapidly to a stop. Moreover two active

muscles at the end of the movement act as a damping device due to the steep negative slope of the force-velocity relation around zero-velocity (Katz, 1939; Jørgensen, 1976).

As movements seem to be preprogrammed for at least 100 ms, assessed load values are used in constructing these programs. It seems that for fast movements loads are taken into account by changing the timing. It is very noticeable that the subject easily adapts to such an unnatural situation as an artificially decreased inertia of his arm.

In violin playing the initial acceleration and velocity of the movements are found to depend on the overall rate chosen for the duration of the tune. For a particular tempo, initial muscle forces for left hand positioning are constant. They are independent of the size of the position change to be made (Fig. 14). However, when another tempo is prescribed it is found that the intensity is changed and the timing is adjusted accordingly (Fig. 17) (Wadman, Denier van der Gon, Monné & Nicolai, 1977).

In summary, it seems that for accurate goal-directed movements a kind of muscle activation level is chosen, depending on load and desired overall tempo or effect. The timing of the muscle actions is then programmed over a period of at least 100 ms, taking into account the activation level.

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