

STIFFNESS CONTROL AFTER FAST GOAL-DIRECTED ARM MOVEMENTS

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Mechanical parameters of the effector system directly after the termination of fast goal-directed arm movements were studied.

Subjects were asked to move their hand as fast as possible to a target the instant the target was presented. Only movements of the subjects' forearms were allowed. They were also instructed not to react actively to forces applied suddenly to their forearm after the movement. As a result of such a force pulse the arm moved to a new position. The apparent stiffness, i.e. the quotient of the applied force and the resultant change of position, was measured. This stiffness is a measure for the resistance of the forearm to externally applied mechanical disturbances.

It was found that after the arm has reached the target the apparent stiffness decreases as a function of time. This is in agreement with the declining amplitude of the electromyographic activity of the muscles that effect the movement.

Arguments are given to support the hypothesis that this apparent stiffness control is part of the motor programme for movements of the forearm, i.e. the stiffness is planned together with the movement.

Introduction

Fast goal-directed movements have long been a subject of interest (Wacholder and Altenburger 1926; Terzuolo et al. 1973; Angel 1975; Wadman et al. 1979). Up till now the research on this subject has concentrated mainly on timing patterns of electromyographic activity of the muscles, velocity patterns and trajectories. Little attention has

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been paid to mechanical properties of the effector system or possible changes of these properties (e.g. apparent stiffness) when a movement is executed.

It is known that reflex sensitivity changes before, during and after a movement (Bonnet and Requin 1982; Erkelens and Bosman 1983; Agarwal and Gottlieb 1980; Wadman et al. 1980; Wieneke and Denier van der Gon 1974). In a recent paper (Vincken et al. 1983) we have shown that it is mainly reflex activity which determines the stiffness of the effector system. Consequently, it is to be expected that apparent stiffness too is subject to changes before, during and after the movement. Control of the stiffness and possibly of other mechanical properties of the effector system might be an essential and functional element in such a movement.

In this study we have tried to obtain an answer to the following questions: Do mechanical properties of the effector system indeed change together with the movement? And if so, can control of these properties be regarded as part of the motor programme?

One method of investigating the apparent stiffness of the effector system is to measure so-called invariant characteristics (Fel'dman 1966a, 1966b, 1980a, 1980b). If a sudden disturbance in the form of a force pulse is applied to the forearm of a subject and the subject is instructed 'not to intervene or correct actively' for this unexpected force, the arm will reach a new equilibrium position. The forearm displacements in response to various values of the applied force can be plotted as a curve in the force-position plane. This curve is called an invariant characteristic. The slope of this curve is the apparent stiffness. The slope is to be interpreted as being related to the overall reflex gain (Vincken et al. 1983). By measuring invariant characteristics directly after a movement we obtain information about the apparent stiffness of the system after the movement, the time dependence of the apparent stiffness and its possible correlation with e.g. the electromyographic activity of the muscles. We did not try to measure stiffness directly before or during the movement, since in that case no equilibrium positions are reached. This hampers the experiment as well as its interpretation.

Methods

Experiments were performed on 7 healthy subjects.

The subjects sat in a chair at a table with their right forearm in a

mould. They could not see their forearm due to an intervening screen. The mould was connected to an axis of rotation coinciding with the elbow joint axis. Thus the only movements of the forearm allowed were rotation movements around the elbow joint. The position of the forearm was measured with a potentiometer mounted on the axis. 384 light emitting diodes (LEDs) mounted on $\frac{3}{8}$ of the circumference of a circle whose radius was 41.2 cm and whose centre coincided with the elbow joint axis were used to present targets and to indicate the position of the arm. The arrangement of the LEDs was such that targets could be presented in the range between 180 degrees (full extension of the forearm) and 45 degrees. The subject could not see his arm but he could be informed about its position by a dimly lit LED. This LED was switched off the instant a brightly lit LED indicating the target had been presented. During the movement and the time while the disturbances were being applied the arm position was not visible to the subject. In this way the subject was prevented from using this information to correct for the departures from the position that he intended to take up. After 2.5 sec the target light was switched off and the LED indicating the arm position was switched on again. The subject was instructed to move his arm to the initial position.

The forces were applied with a motor that was connected to the axis of rotation by means of cogwheels and a chain. They gave rise to torques that rotated the forearm in flexion or extension direction. These torques were measured with strain gauges attached to the axis. It was checked that the torques did not change as a result of the change in the position of the forearm.

A Motorola 6809 μ -processor was used to control the experiments.

In the experiments subjects were instructed to move their forearm as fast as possible from the starting position to a target as soon as the LED indicating the target was lit. The target could be one of four target lights (chosen from the 384 possible targets) and these were presented in a random sequence at a random intertrial interval of 5 to 7 sec. During one experimental session 256 movements had to be made and in half of these a disturbing force pulse lasting between 1.2 and 1.8 sec was applied. After this, the disturbance was made zero again. After another 0.5 sec the target light was switched off.

The disturbing force pulse could have one of eight possible values in the range of 0.2 to 5.0 Nm and it was applied at one of four possible instants after the onset of the movement. The onset of the movement

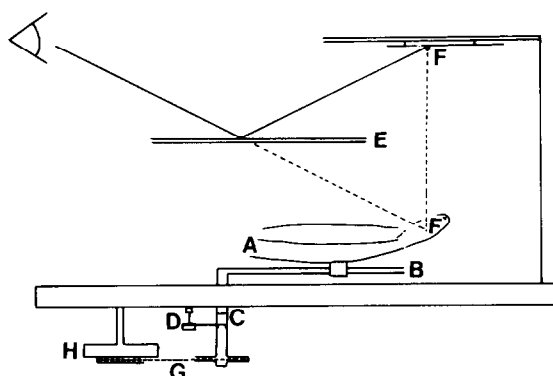


Fig. 1. Cross section through the mechanical part of the apparatus. A, arm mould; B, Pivoted bar; C, Strain gauges; D, Potentiometer; E, Perspex screen; F, Light emitting diodes; F', Image of F in the screen; G, Cogwheels + chain; H, Motor;

was defined as being the instant at which the difference between the starting position and the actual position of the hand exceeded a value of 1 degree. After the movements had been recorded for three minutes the subject was allowed to rest for three minutes. A session lasted about an hour.

From 0.1 sec to 2.5 sec after the presentation of the target the position of the forearm, the applied force and the electromyographic activity of biceps and triceps were measured at intervals of 10 msec. The electromyographic activity was obtained by means of surface electrodes placed over the muscle belly. The signal was sent through a low-pass filter with a 3 dB cut-off frequency of 3 Hz in order to show only the general course of the activity.

The Motorola μ -processor provided the stimulus generation and performed the data sampling. As a result of the applied force pulses the forearm of the subject moved to another position, and thus invariant characteristics (i.e. the relation between the applied force pulse and the resulting shift in position) were established at different instants after the onset of the movement. The apparent stiffness can be deduced from these curves in the torque-position plane.

Results

It turned out that the maximum velocity of subjects' movements when the instruction 'move as fast as possible' was given ranged from 400 degrees/sec to 500 degrees/sec.

In fig. 2, an average of eight movements to a target is shown. These were undisturbed movements in extension direction. The upper two traces show that average agonist and antagonist electromyographic activity is still present after the target has been reached. The time

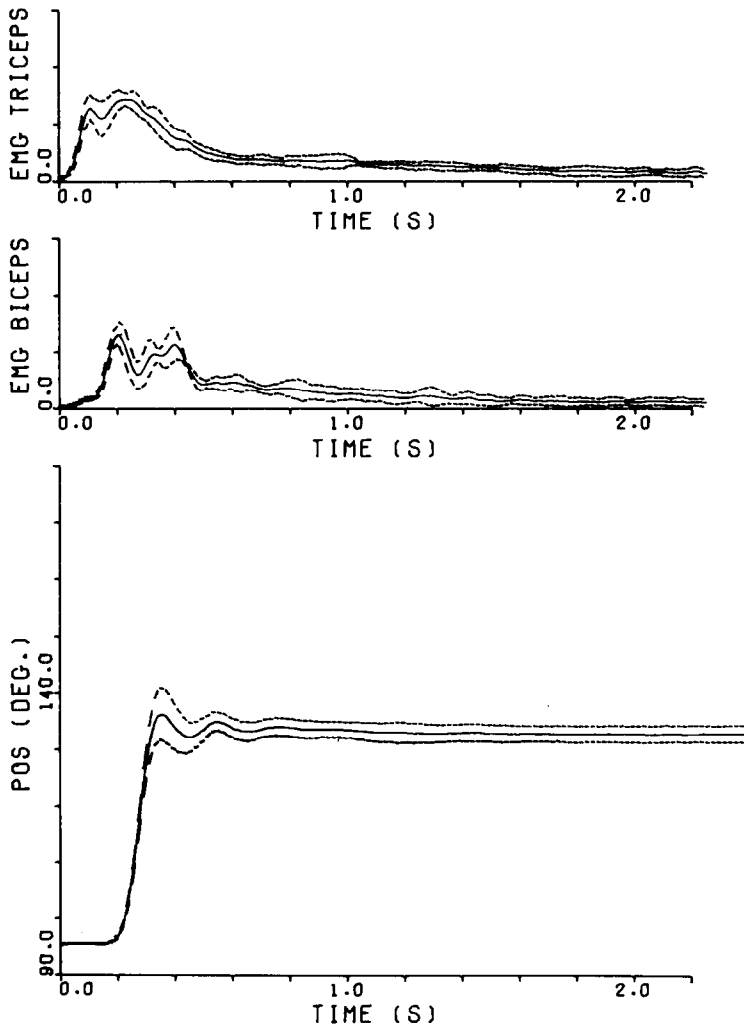


Fig. 2. Average of eight movements to target. The two upper traces show activity of biceps and triceps during and after the movement expressed in arbitrary units. Because of the low-pass filtering, peaks in the EMG are not very pronounced. The lower trace represents the position as a function of time. The dashed lines in these graphs indicate the average signal + or - the standard deviation. Position is measured in such a way that 180 degrees correspond to full extension.

constant with which this EMG activity declines is of the order of 0.5 sec. Peaks in the activity are not very pronounced due to the low-pass filtering. The average end-position and the standard deviations when force pulses were applied and withdrawn again did not differ significantly from end-positions and standard deviations in cases where no force pulses were applied. This indicates that the instruction 'do not intervene or correct actively for the applied force pulses' was indeed obeyed.

In fig. 3, three movements to the same target are shown. The disturbing torque pulses, which had the same value in the three recordings, were applied at three different instants after the onset of the movements. A striking effect in these recordings is the fact that as long as the force is acting on the forearm the arm keeps on moving, be it slowly. Consequently, invariant characteristics should be determined at fixed instants after the onset of the movement.

Fig. 4a shows an example of an invariant characteristic. Displacements were measured 0.9 sec after the onset of the movement. Different

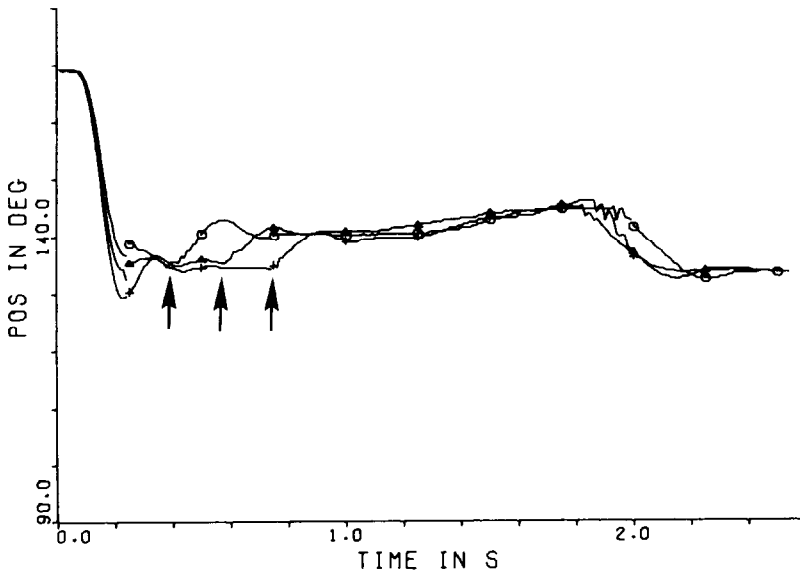


Fig. 3. Three single movements to the same target. After the movement disturbances in the form of torque pulses of the same amplitude were applied at different instants (indicated with arrows, 320 msec, 480 msec, 640 msec after the onset of the movement).

symbols in the plot denote the results for different instants at which the torque pulses were applied. When the invariant characteristic is measured at a later instant with respect to the onset of the movements (1.5 sec as in fig. 4b) the deviations from the intended positions are larger, resulting in a less steep invariant characteristic.

We calculated the slopes of the invariant characteristics by calculating linear regression lines for each group of eight points in the plot. The slopes of these lines give an overall indication of the steepness of the invariant characteristic and thus of the apparent stiffness of the effector system.

Fig. 5 shows for one subject the slope of the invariant characteristic as a function of the time that has elapsed since the onset of the movement. It can be deduced from this figure that the decay of the apparent stiffness occurs with a time constant of about 1 sec.

We found similar results for other subjects. The extent of the effect varied between subjects, but in general the apparent stiffness decrease

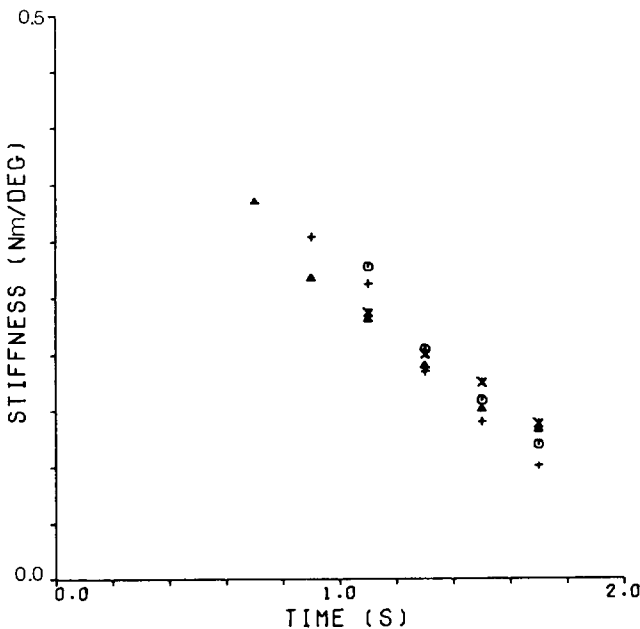


Fig. 5. Slope of the invariant characteristics as a function of the time that has elapsed since the onset of the movement. Torque pulses applied at 320 msec (○), 420 msec (Δ), 480 msec (+) and 640 msec (×) after the onset of the movement.

was not as sharp as shown in fig. 5. The velocities of the goal-directed movements, however, were similar for most subjects. Some subjects showed steep invariant characteristics. Possibly, they make movements with tense muscles, whereas others who showed less steep invariant characteristics would make movements with more relaxed muscles (Fel'dman 1966b). Both types of subjects, however, showed that the apparent stiffness around the elbow joint was time-dependent. The values for this dependence were between $0.23 \text{ Nm/degree} \cdot \text{sec}$ and $0.04 \text{ Nm/degree} \cdot \text{sec}$.

Results for a subject obtained in several experiments are highly reproducible, indicating that the apparent stiffness is controlled connected to the movement according to a fixed pattern. The movement distance and the direction of the movement had no influence on the effects. Fig. 6 shows three movements to the same target but starting from different positions.

One variable in our experiments the consequences of which have not yet been commented upon in the presentation of the results is the instant at which the torque is applied. From fig. 3 it is clear that the

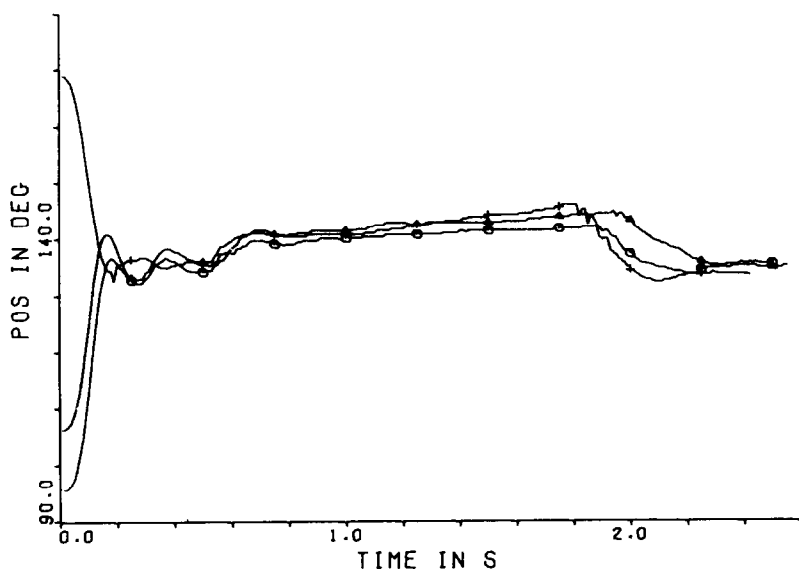


Fig. 6. Three movements to the same target starting from different positions. The three position traces coincide after the torque has been applied, indicating the the movement distance or the movement direction are not determinative for the apparent stiffness after a movement.

departures from the position that the subject intended to reach do not depend on this instant since, after the instant the force pulses are applied, the three traces coincide. Differences do not exceed standard deviations as determined in repeated trials. This again indicates that the change in the apparent stiffness is coupled to the movement and not to the instant at which the torque is applied. This is also obvious from figs. 4 and 5, where different symbols are used to discriminate between experiments in which the torque was applied at different instants. The change in apparent stiffness manifests itself as a change in position as long as the torque is acting on the forearm. As soon as the torque is set to zero again, the arm of the subject moves back to the position that the subject had intended to reach and remained there.

Discussion

In this paper we examine the control of apparent stiffness around the elbow joint in relation to movements of the forearm. The first result emerging from the experiments is that the apparent stiffness decreases as a function of the time that has elapsed since the onset of a movement. This can be concluded from the slopes of the invariant characteristics determined at different instants with respect to the onset of the movements. In a recent study (Vincken et al. 1983) we have shown that apparent stiffness is for the most part due to afferent feedback signals. So a declining apparent stiffness would correspond to a decreasing gain of the feedback loop.

It may be argued that the decline of the apparent stiffness is only a result of the declining activation in the muscles. However, small changes in the EMG after the application of the disturbing force, indicate that reflex contributions are present.

Supposing that the receptors evoking the afferent activity are muscle spindles, then there are at least two possible channels for the adjustment of the feedback gain, the static and the dynamic γ -efferents. The static γ -efferents are likely to be involved in the actual positioning of the limb. The dynamic γ -efferents may be responsible for the gain adjustment of the feedback loop (Appenteng et al. 1980). It can also be seen from single movement recordings that the gain of the feedback loop and thus the apparent stiffness changes. As long as the force is acting on the forearm the arm keeps on moving.

According to our measurements, the apparent stiffness does not

depend on the instant at which the disturbance is applied (figs. 3, 4 and fig. 5). It was found that the apparent stiffness and the decay of the apparent stiffness are coupled to the movement. This would imply that the gain adjustment is part of the activation pattern of the movement. The reproducibility of the measurements also gives an indication for a fixed pattern time-locked to the movement. Stiffness control is in our view part of the motor programme.

Indirect arguments supporting this view are that the apparent stiffness regulation (a) may be effective in case of misjudgements of the load against which a movement has to be carried out and (b) also that it may play a role in stabilizing the limb after a movement.

Observations of electromyographic activity of biceps and triceps in flexion and extension movements show a declining amount of activity after the target has been reached (fig. 1); (Wadman et al. 1979; Lestienne et al. 1981). This is in agreement with the declining apparent stiffness. It is well known that when the force exerted by the muscles decreases, reflected in a declining electromyographic activity, the gain of the reflex also decreases (Wadman et al. 1980). The time constants of the decay of the apparent stiffness and of the electromyographic activity, however, are somewhat different. The known relation between muscle activity and feedback gain is not unique. This is clear from experiments in which subjects are instructed in two different ways: not to react to the disturbance (let go) or keep your arm in the position it is now (hold on). In neither case were the subjects to activate their muscles beforehand. No electromyographic activity can be detected before the disturbance. Nevertheless, there is a considerable difference in the gain of the reflex loop (Wadman et al. 1980).

It can be argued that the decline of the apparent stiffness after a movement is dependent on the instruction given to the subject. The only instruction given was 'move as fast as possible and do not react to sudden disturbances'. The influence of other instructions (e.g. concerning the velocity) will be dealt with in a subsequent paper. In any case movement distance is not a main determinant of the apparent stiffness after a movement.

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