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STIFFNESS AS A CONTROL VARIABLE IN MOTOR PERFORMANCE

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In the experiments described in this article we investigated the control of stiffness of the effector system in relation to parameters of the movement. If the velocity of a movement is chosen, it appears that at the same time the stiffness of the effector system is set to a preferred value. By changing the instruction given to the subject it is possible to change the relationship between velocity and stiffness without changing the kinematic parameters of the movement.

Finally, the changes of stiffness and velocity in a learning process are studied. In conformity with what might be expected on intuitive grounds, it is found that velocity increases spontaneously during learning while stiffness decreases. The results are discussed in connection with the generation of motor programmes.

Introduction

In a recent study (Vincken et al. 1984) we investigated stiffness control after fast goal-directed arm movements. Stiffness was measured as the inverse of the displacement caused by a disturbing force. It appeared that the decrease of stiffness after a fast movement is time-locked to the movement. We concluded that this decrease in stiffness is mainly caused by a decrease of the gain in reflex loops and that this control is to be considered as part of the motor programme for a movement.

So far, we have investigated stiffness only in relation to movements that are made as fast as possible. Since stiffness changes with the extent of activation (Fel'dman 1966), caused both by the direct activation of the muscles and by the accompanying increase in reflex gain (Wadman

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et al. 1980) it can be expected that stiffness will be smaller when movements are made more slowly. The aim of the present study is to investigate whether and in what way stiffness changes in relation to movement velocity. The spontaneous relationship between stiffness and movement velocity can, it is proposed, be influenced by the instruction given to the subject. When he is instructed to coactivate the muscles involved in the movement a greater stiffness of the effector system might be expected.

Our interest in the relationship between stiffness and movement velocity originates from the intuitive notion that velocity and stiffness change in opposite directions during a learning process (velocity increases while stiffness decreases). When a subject is learning to make a complicated movement he will perform slowly in the beginning, with tense muscles, prepared for corrections if these are needed. In the course of a series of movements, performed in order to master the movement, stiffness of the effector system will decrease while the velocity of the movement increases. The view that the above-mentioned features indeed express an increase in skill is supported by several studies (van Dantzig 1953; Denier van der Gon 1969; van der Tweel 1969; Denier van der Gon 1979).

The experiments described in this paper are carried out to provide evidence for these ideas. The first experiment is carried out merely to show how stiffness after a movement changes with the velocity of the movement and with the extent of coactivation of the muscles generating the movement. These experiments are similar to those described in our earlier paper (Vincken et al. 1984).

In the second experiment we try to obtain some support for the suggestion that the stiffness of the effector system decreases naturally in the course of an experimental session in which a subject practises to make a complicated movement. We asked subjects to draw a complicated figure. The size of the figure was such that the whole arm was involved in the movement. By applying force pulses and evaluating the resulting response of the effector system, we checked whether the apparent stiffness indeed decreased as a function of the number of performances carried out.

Stiffness is rather important in this context since changes in stiffness are related to changes in the ease with which a movement is made. A movement made with tense muscles is more energy-consuming and will lead to fatigue sooner than a movement made in a more relaxed way. If we understand how a certain parameter (e.g., stiffness) changes in the course of the learning process, we may be able to use this change as a measure for the extent of progress. In this way learning paradigms can be evaluated more easily.

Methods

Experiment 1

In these experiments experimental conditions and the apparatus used are the same as those described in our earlier papers (Vincken et al. 1983, 1984). The subject was seated in a chair, his forearm in a mould allowing only rotation movements in a horizontal plane around the elbow-joint. With help of a DC torque motor connected to the axis of rotation by way of cogwheels and a chain, disturbing moments could be applied to the forearm. The value of the disturbing moments was measured with strain gauges attached to the axis of rotation. The subject could not see his forearm directly. Targets were presented by way of 384 light emitting diodes (LED's) arranged on $\frac{3}{8}$ of the circumference of a circle (radius 41.2 cm), the centre of this circle coinciding with the elbow joint. These LED's are also used for the presentation of visual information about the position of the subject's forearm. No visual information was supplied during and directly after the movement to prevent the subject from using this information to correct for the deviations caused by the disturbing moments. As soon as the target light appeared, the subject had to obey one of the following instructions:

- move as fast as possible, but before, during and after the movement coactivate flexor and extensor muscles;
- move with a velocity of your own choice, but try to make the movements in one session with the same velocity;
- move with a velocity of your own choice, but before, during and after the movement coactivate flexor and extensor muscles;
- move as fast as possible, but as soon as the target is reached relax immediately.

Instructions were not randomized. The subject was allowed to practice the movement in one condition before the actual recording took place. In each condition a total of 24 responses, in which the moment had eight possible values (ranging from 0.2 to 5.0 Nm) and was applied on three possible instants (320, 480 and 640 msec) with respect to the onset of the movements, were collected. In this experiment, subjects had to make movements to only one target and during all responses disturbing moments were applied. In all the above-mentioned conditions subjects were instructed 'not to react actively to correct for the disturbances'. For a more detailed description of the apparatus and procedures see Vincken et al. (1984).

Five subjects, aged 28 to 55, participated in these experiments.

Experiment 2

Five subjects, aged 8 to 48, who were not familiar with the purpose of the experiment, participated. They were instructed to draw a figure inside a framework according to an example shown to them on a piece of paper. We chose the drawing of a figure (the G-clef, of which subjects had no writing experience) as an example of a complicated movement, because the visible result would provide both the subject and the experimenter with an outcome to evaluate. The figure to be copied had dimensions of 8×25 cm so that the subject had to make the movement with his arm. The subjects were told:

- where to start within the framework;
- roughly what the size of the figure had to be;
- to draw the figure fast and accurately;
- to try not to intervene to correct for the force pulses when these were applied.

About two seconds after an attention signal was given the subject had to start the movement. The figure was drawn with a pencil to which an infrared light emitting diode (LED) was attached. The position of this LED was sampled with a commercially available 'Selspot' system (Selcom AB, Sweden: a two-dimensional lateral photodetector, fitted in a camera (Canon, lens 50 mm 1 : 0.95)). Data were sent to a computer for off-line processing. When a subject had almost completed the movement, and his arm had not yet come to a standstill in the end-position a force pulse (2 N, 0.5 sec) could be generated with a DC torque motor. The movements were disturbed by means of a long rope attached to the torque motor and to the wrist of the subject. The force pulse acted in a direction perpendicular to the movement direction. The disturbance was not applied during all performances, but at random; on average, one out of three movements was disturbed. In total, subjects had to draw 100 copies of the figure. An experimental session lasted about 25 minutes. The experiments were controlled by a 6809 μ-processor, which also performed the data-sampling.

Results

Experiment 1

In these experiments we investigated the dependence of stiffness on the instruction given to the subject. Typical results are summarized in figs. 1 and 2.

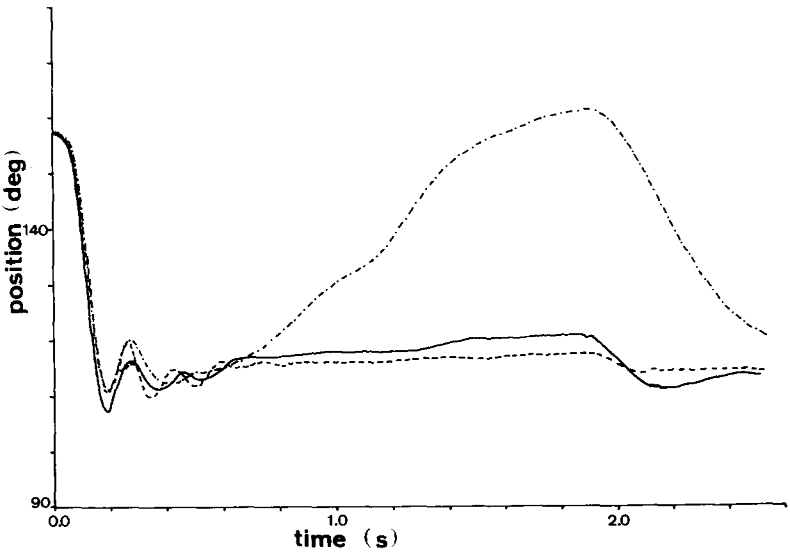

Fig. 1. In this figure three responses of a subject are shown when he was instructed to move to the target: (a) as fast as possible (———); (b) as fast as possible with coactivation of flexors and extensors (- - - -); (c) as fast as possible but to relax as soon as the target was reached (–·–·–·–). The moment, which was 1.8 Nm, was applied 480 msec after the onset of the movement.

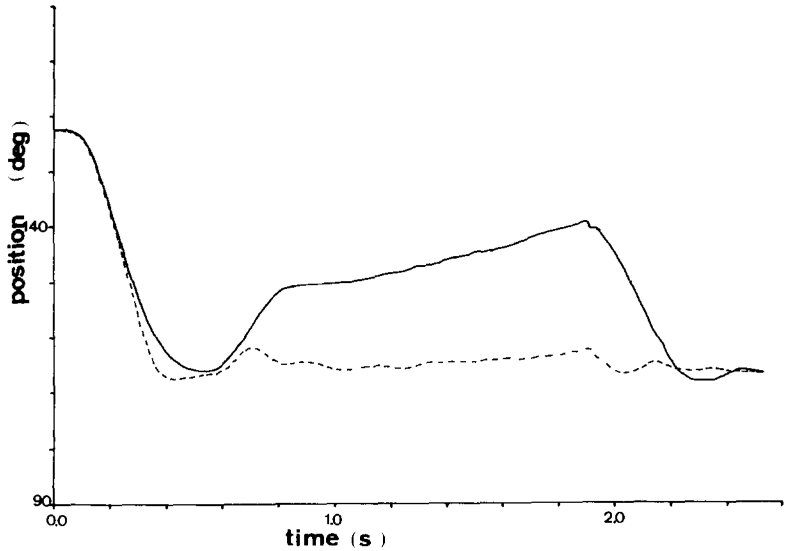

Fig. 2. Two movements to the same target made by the same subject as in fig. 1. Now the subject could move with a velocity chosen by himself. The dashed response was obtained when the subject also had to coactivate flexor and extensor muscles. The moment, which was 1.8 Nm, was applied 480 msec after the onset of the movement.

Fig. 1 shows three flexion movements made with maximum velocity to the same target. The differences between them result from different instructions given to the subject. The maximum velocity was the same for these responses. The departure from the intended end-position was smallest when the subject was instructed to move as fast as possible and to coactivate flexor and extensor muscles before, during and after the movement. When no special instruction was given, only 'move as fast as possible', the departure from the end-position was larger. The third line represents the response when the subject was instructed 'to move as fast as possible and to relax as soon as the target is reached'. The departure was much larger in such cases.

Fig. 2 shows the responses when the subject was instructed to move with a velocity chosen by himself. The recording shows that the departure was not as large as when he had to relax directly after a movement made with maximum velocity. When an additional instruction (coactivate flexor and extensor muscles) was given, the departure was again of the same magnitude as that in fig. 1 where the movement was made as fast as possible and also both muscles were coactivated.

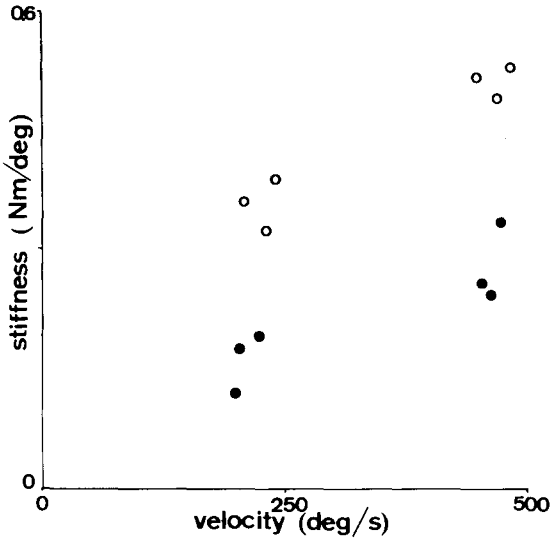

Fig. 3. Stiffness at 1.5 sec after the onset of the movement as a function of the velocity with which the movement is made. ○ and ● denote two different subjects.

The value of the moment step was in these conditions 1.8 Nm. As long as the moment was acting on the forearm, the arm kept moving, indicating a decrease in the stiffness related to the movement (figs. 1, 2; see also Vincken et al. (1984)). Results for the other values of the moments showed the same tendency: displacements increased linearly with the disturbing moments.

Stiffness can be determined by calculating the slope of an invariant characteristic (= the relation between displacements as a result of disturbing moments and the disturbing moments; see also Vincken et al. (1984)) measured on a fixed instant with respect to the onset of the movement. In case of maximal velocity, stiffness for different subjects ranged from 0.15 to 0.67 Nm/deg.

In fig. 3 stiffness is shown as a function of the velocity with which the movement was made.

Summarizing, we can say that stiffness is related to the velocity of the movement. When a subject is instructed to make a movement with a lower velocity stiffness is also reduced. Coactivation of the muscles involved in the movement results in a greater stiffness.

Experiment 2

Fig. 4 shows two copies of a drawing made by an eight-year-old child. These results were obtained in a session in which no disturbing forces were applied. Yet, the copies show the other features mentioned in the introduction; a less hesitant performance and a decreased movement time after practicing. The latter finding was corroborated by the actual measurement of movement time.

Fig. 5 shows an example of a recording of a disturbed and an undisturbed movement made by an adult subject. The disturbance is applied at the end of the movement when the end-point is about to be reached.

In fig. 6 the deviation caused by the force pulse at the end of the movement is shown as a function of the performance number for the same subject. The deviation is measured as the distance between the positions of the LED at the beginning and at the end of the force pulse in the direction in which the force pulse acted (A–B in fig. 5). The trajectory of the LED as a result of the force pulse was more or less a straight line. It is obvious that as the subject practises more the deviations become larger. This is in agreement with our idea that stiffness decreases with practice.

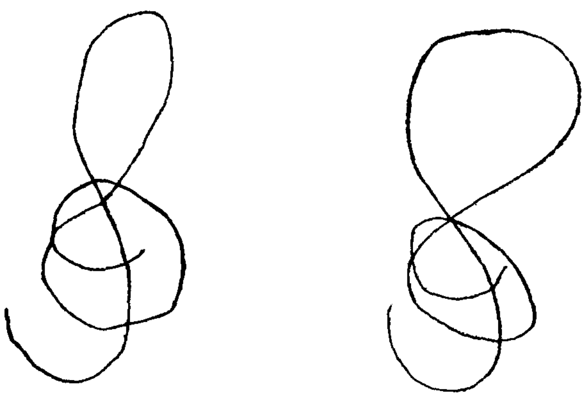

Fig. 4. Two copies of a drawing of a musical clef by an eight-year-old child. The left drawing is one made at the start of a session in which the child learned to draw the figure. The drawing at the right is one made at the end of a sequence of 50 performances. Lines in the right drawing are smoother and less hesitant than those in the left drawing.

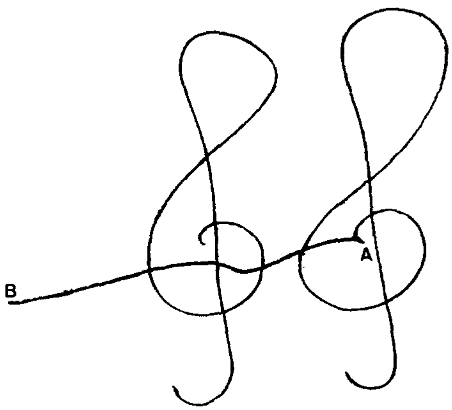

Fig. 5. Two copies (disturbed and undisturbed) of a figure made by an adult subject when a force pulse was applied at the end of a movement. The deviation is measured as the distance between A and B, the positions of the pencil point at the beginning and at the end of the force pulse.

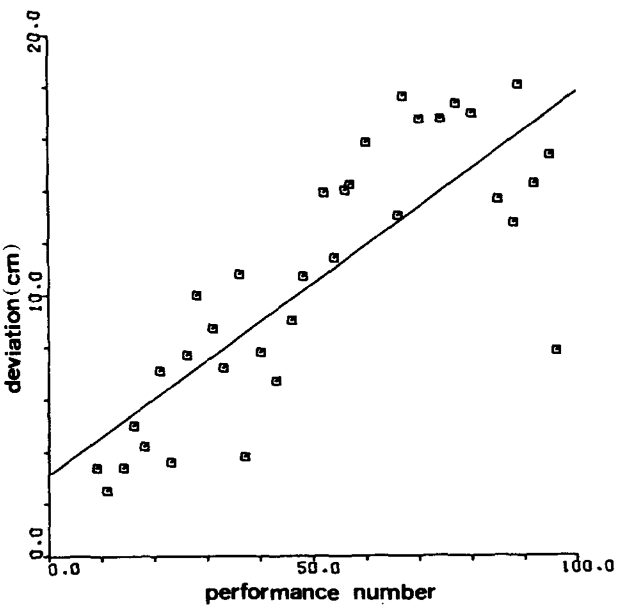

Fig. 6. Deviations as a function of the performance number. The line indicated in the figure is a linear regression fit to the data points. See text.

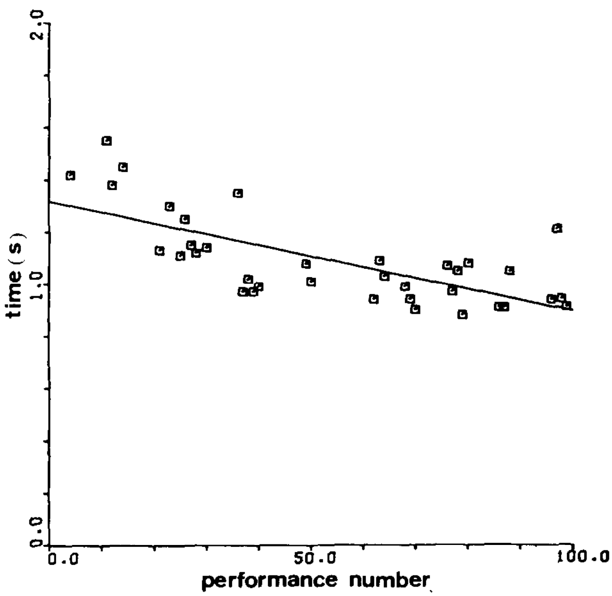

Fig. 7. The time needed to complete the movement as a function of the performance number. The line is a linear regression fit to the data points.

Fig. 7 shows that the time needed to complete the undisturbed movement decreases as the subject becomes more practised. The movement time is defined as the time elapsed from the moment that the velocity of the LED attached to the point of the pencil was significantly different from zero until it was zero again. The movement time is a measure for the overall velocity with which the movement is made. It is clear from figs. 6 and 7 that the change in stiffness is more pronounced than the change in velocity. The other three adult subjects showed similar results. In sessions with different subjects changes of stiffness of a factor of 3 to 6 were found.

To check whether we are really dealing with a learning process in this experiment we asked one subject to draw the figure again four days after he had practised it during a session of 75 performances. The subject was instructed as before but this time he had to make only 25 movements, some of which were disturbed. The results of this experiment are shown in fig. 8, together with the results of the first experiment.

During the first 75 performances stiffness decreased. The results of

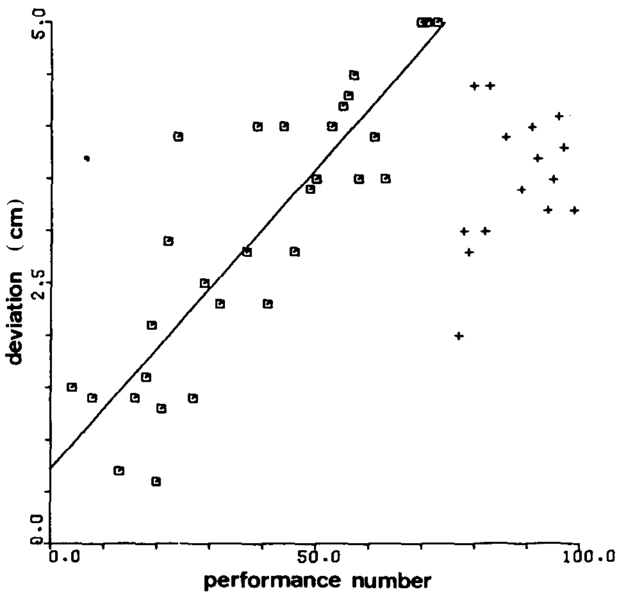

Fig. 8. Results for another subject as presented in fig. 6. Deviations as a function of the performance number. The squares indicate the results of the first experiment, the line is a linear regression fit to the data points denoted by the squares. The crosses represent the results of the same experiment done four days later.

performance 76 to 100 are indicated with another symbol. It appears that, after four days, stiffness is still less (deviations as a result of a force pulse are larger) than it is at the start of the first experiment. The actual drawings (not shown here) reveal smoother and less hesitant movement trajectories. This made us conclude that the process we were studying was indeed a learning process in which a skill was gradually mastered.

Discussion

From the results of experiment 1 we conclude that when the subject chooses the velocity of the movement, the stiffness of the movement is also established. This is so when no other instruction is given. In programming the movement subjects have the possibility to uncouple control of the velocity of the movement and the stiffness. This can be seen in fig. 1 where the subject is instructed to move as fast as possible but also coactivate his flexor and extensor muscles before, during and after the movement or relax as soon as the target is reached. The kinematic features of the movement remain the same as before when only the instruction 'move as fast as possible' is given. Drastic changes in the response to the moment pulse show that the stiffness and thus the adjustment of the gain of the reflex loop definitely differs from that in the former condition.

The fact that most features of the movement remain the same while one aspect, the stiffness after the movement, changes drastically indicates that a versatile mechanism is responsible for the generation of movements in the central nervous system. A possible realization of such a mechanism may be the following: A stimulus generates an imaginary representation of the movement ('trace') that has to be made in response to the stimulus. This trace is scanned and thus a kind of imaginary movement is carried out. A motor programme for the real movement is deduced from this imaginary movement. By controlling the velocity of the scan the central nervous system controls the velocity of the real movement. The same or other scaling factor may control the adjustment of the reflex loops and thus parameters as, e.g., the stiffness. This concept is related to, but has a number of advantages over the so-called general programme idea (Schmidt 1975, 1976). According to this idea a programme for a class of movements is stored somewhere in the CNS. After adding some parameters, special for the actual response, this programme may be put into effect when needed. In our view it is not likely that the CNS operates with such stored programmes. The system is probably more flexible and can easily cope with movements that have never been made before. This is the reason for proposing a kind of trace-scanning mechanism that may generate a programme. This concept is in agreement with the observation that if a movement is made faster, it is as if the movement pattern is compressed (Viviani and Terzuolo 1980, 1982). The fact that in our results velocity and movement pattern remain the same while the stiffness can be influenced by adding an instruction, is compatible with this concept.

The possibility to change one parameter while leaving the other features intact may be useful when movements are learned. At the beginning of a series of new complicated movements a subject performs slowly, with a stiff effector system so that disturbances do not have drastic consequences for the result. In these slow performances the subject masters the spatial aspects of the movement and in a later stage he can increase the movement velocity and decrease the stiffness of the system. In experiment 2 we found indications for the correctness of this idea.

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