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Invariants in Loaded Goal Directed Movements

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Abstract. Goal directed movements, executed by means of a manipulator with various dynamics, were investigated in order to establish to what extent the loading affects the executed movement. The desired movement concept, together with a describing function model for goal directed movements, was applied to parameterize the movements. Analysis of the results showed that the position trajectories, when scaled by means of a fundamental scale property, with respect to the maximum velocity of the desired movements, were invariant under variation of the manipulator dynamics. From this invariance in the phasing of the movements, it was concluded that the subjects fully adapted to the applied loads.

1 Introduction

The accurate execution of a prescribed position trajectory by a manipulator with given dynamics, such as in tracking tasks, requires the production of a force trajectory which is completely specified by the dynamics of the manipulator and the movement to be produced. If the same trajectory has to be executed by means of a manipulator with different dynamics, then the force trajectory has to be changed according to these dynamics. E.g. a spring loading would require a force proportional to the position, whereas a movement loaded by a mass would require a force proportional to the acceleration of the movement.

To what extent the force trajectory is adapted to the new dynamics can be analyzed by comparing the actually executed movements and the prescribed movements for different manipulator dynamics. This approach, mainly based on the analysis of tracking errors, has been applied in many researches (Magdaleno and McRuer, 1966; Kruger, 1978; Notterman and Weitzmann, 1981) in order to investigate the influences of proprioceptive feedback in tracking movements.

In voluntary goal directed movements, however, only the position of the target is given, whereas the position trajectory that has to be followed to reach the target is not specified. As a consequence, in voluntary movements the subject has to develop its own strategy to guide and control the movements (self paced movements).

The absence of an external reference, according to which the movement has to be made, hampers a direct application of the tracking error approach in establishing the influences of different manipulator dynamics. Apart from this methodological difficulty, the variability of goal directed movements in a given motor task, due to e.g. fluctuations in the subjects control strategy, imposes another problem in the analysis of the influences of different loadings on goal directed movements.

In the sequel, it will be argued that, under suitable assumptions, goal directed movements in a well defined motor task can be described adequately by means of a so-called desired movement. This desired movement, as calculated from the recorded movements, can be seen as an estimation of the representation of the internal reference as adopted by the subject during the execution of the movements; the variability of the successive movements can be interpreted as random variation of the desired movement. Then the influences of different manipulator dynamics on voluntary movements can be established by comparing the resulting desired movements. The comparison, however, requires an adequate parameterisation of the desired movements. This can be conceived by means of a describing function model for goal directed movements, which provides an accurate fitting of the movements. The experimental evidence, as will be

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presented, shows that the dynamics of the manipulator, by which the movements are made, differ both with respect to the order and to the actual values and hence the executed force trajectories clearly differ. However, the position trajectories, when scaled by means of a fundamental scale property, are invariant to the manipulator. From these results it was concluded that the subject fully adapts to the applied manipulator dynamics in order to keep the same (scaled) position trajectory.

1.1 Desired Movements

When accurate, reproducible, goal directed movements have to be made by means of a manipulator with certain dynamics, it can be assumed, that the subject, after some training, is aware of the bandwidth limitations in the displacement of the manipulator: the subject knows, that for a given force trajectory the displacement is limited to a given position trajectory. In reverse, it can be assumed that the subject is aware of the required force trajectory that should be exerted onto the manipulator to produce a given position trajectory i.e. the subject has obtained an internal representation of the manipulator dynamics, in which the limitations with respect to the speed of the response are taken into account.

Therefore, when a goal directed movement has to be executed, a distinction between on the one hand the objective error, the difference between the task input, the size of the step, and the task output, the actuale movement, and on the other hand, the subjective error should be made. The subjective error is the difference between a certain desired movement and the actual executed movements. Apart from the before mentioned bandwidth limitations, the desired movement will depend on the notion the subject has about his task. This notion concerns aspects like the speed of the response, the response accuracy and the effort. The relation between the task input and the desired movement can be considered as the subjects internal representation of the task of which the internal representation of the manipulator is a part. Differences between the actual movements are in fact deviations from the desired movement. They may result from actual fluctuations in the internal representation of the task (i.e. the force trajectory is not reproduced exactly, due to e.g. an imperfect internal representation of the manipulator) and from external disturbances such as a change in the manipulator dynamics or a sudden change in the visually perceived information about the position.

In the sequel, it will be assumed that the internal representations can be modeled (Veldhuyzen and Stassen, 1977): the internal representation of the task is modeled by the Internal Model of the Task (IMT), whereas the internal representation of the manipulator is thought to be modeled by the Internal Model of the Manipulator (IMM).

Although the above discussed concepts are hypothetical and although they only serve as a tool in the analysis of the movements, these concepts are closely linked to current ideas on motor behaviour (Vincken, 1983).

In order to specify the desired movements, we consider the case that no external disturbances are applied. Then, the differences between the actual movements can be attributed to fluctuations in the IMT. In general, these fluctuations will be of a random nature, so that the IMT can be considered as a stochastic process with initially unknown properties. Hence, the actual movements are in fact realisations of this stochastic process, triggered by the input step, and of which the mean is specified by the desired movement. This implies that the desired movement can be estimated from a set of actual movements.

From the theory on stochastic processes it is known, (Bendat, 1964; Papoulis, 1965) that the computation of the average in time domain, as an estimate of the mean value of the process is only meaningfull if the process is assumed to be stationary and ergodic; it is however not valid for non-stationary processes. Hence, in order to estimate the desired movement, we have to assume that the IMT, seen as a stochastic process, is stationary.

In view of the present study, this framework enables to study the influences of different manipulator dynamics on goal directed movements in the following manner:

For given manipulator dynamics, the subject has to obtain a stable IMT. Since this IMT not only depends on the applied manipulator dynamics, but also on the subject's notion of the task, both variables should be well defined. Furthermore, in order to allow a comparison of the effects of different dynamics, the instruction as given to the subject should be the same. To allow the subject to obtain a stationary IMT, series of training sessions should be conducted in which reproducible movements are practiced. In this way, the assumed stationarity of the IMT can be met. Then, if only the dynamics of the manipulator are varied, the influences of different dynamics can be studied by comparison of the corresponding desired movements.

As pointed out before, the stationarity of the IMT allows the calculation of the desired movement, defined as the mean of the process, from the recorded movements. It should be stressed that in general, this mean is not equal to the movement that is obtained by averaging, even after synchronisation of actual movements in time; this only holds if the IMT is constant in time which may not be expected. Hence, additional assumptions with respect to the statistical properties of the IMT have to be introduced. Based on the experimental results (Armstrong, 1970; Shapiro, 1976), in which it was shown, that when a movement is made in different movement times, the relative phasing of the movement pattern remains unchanged, it was initially hypothesised that for a stationary IMT in a given motor task only the overall velocity of the movement varies from movement to movement and hence is the random variable of concern. This assumption implies, that, in the noise free case, the resulting desired movement, as the mean of the process, will be purely deterministic. However, analysis of the experimental data yielded that although a significant part of the variability of the movements could be attributed to the variability in the overall velocity, a small variability remained. Therefore, the initial hypothesis was replaced by a less stringent version, in which apart from the overall velocity as the most dominant random variable in the variability of the movements a minor contribution of another, independent, random variable is not excluded. In consequence to this hypothesis, the desired movement as calculated after removal of the variability in the movements due to the variability in the overall velocity, will contain a stochastic component.

2 Methods

In order to investigate the effects of loading on goal directed movements within the frame work as pointed out in the previous section, a number of experiments has been carried out in which subjects performed goal directed movements by means of a manipulator.

2.1 Experimental Set-Up

Figure 1 gives a schematic top view of the experimental setup. A subject is seated in front of a manipulator and a video monitor (67 cm). Righthanded movements are made in the saggital plane by flexion and extension of the upper- and the fore-arm. The manipulator is a linear hydraulic motor, stroke lenght 0.4 m, powered by an oil pump. Specially designed hydrostatic bearings allow a virtually frictionless movement of the manipulator (Viersma, 1980). In time domain the dynamics of the manipulator are given by

Table 1. Intended manipulator dynamics for the different experimental conditions: $x0=0$

Exp. conditions	Mass M [kg]	Damping D [Ns/m]	Spring C [N/m]
$C1$	0.6	0.6	0
$C2$	0.6	10.6	0
$C3$	0.6	3.7	10
$C4$	3.7	10.6	0

$$F(t)=M\ddot{x}(t)+D\dot{x}(t)+C(x-x0)\,. \tag{1}$$

The mass M, the damping D, the spring constant C and the equilibrium position $x0$ can be adjusted electronically. The exerted force is measured by a force transducer, mounted in the handle. The position is obtained from a linear position transducer. The velocity is measured from the servo valve that controls the manipulator, whereas the acceleration is derived by on-line differentiation of the velocity. During the experiments, these four signals, sampled at a rate of 100 Hz in order to allow an accurate estimation of the time delays, were recorded for off-line processing. The actual position of the manipulator, together with the target position were displayed as horizontal bars on the video monitor. This set-up, together with the experiment control computer, is described in more detail elsewhere (Ruitenbeek and Janssen, 1984).

2.2 Motor Tasks

Four different manipulator dynamics were considered (Table 1). The order of the dynamics was established in advance, whereas the actual values of the mass, the damping and the spring constant were selected on the basis of clearly perceptible differences. Each condition was repeated twice in two distinct runs. Each run consisted of 25 goal directed movements. The movement, step size 0.2 m, was initiated by a change of the target position as displayed on the screen, symmetrically around the screen centre. The gain of the displayed position of the manipulator was calibrated to 1. The sequence of the different runs, selected randomly, was preprogrammed into a mini-computer. The computer performed the setting of the manipulator dynamics, the random timing of the target changes, and the data acquisition. Training sessions were conducted in which each

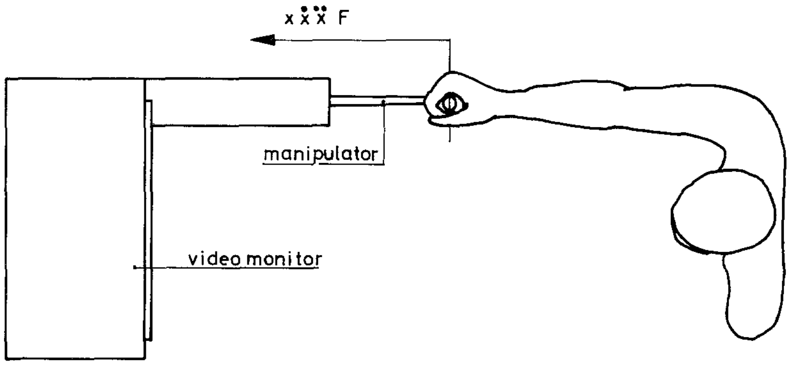

Fig. 1. Schematic top view of the experimental setup for measuring goal directed movements in the saggital plane

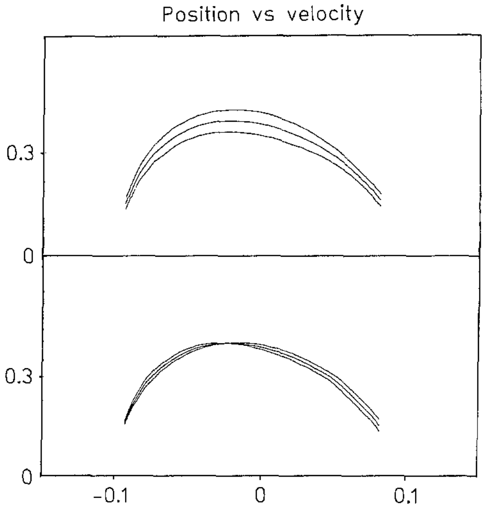

Fig. 2. Average contour and standard deviation of the phase plane plots for unscaled movements *(upper part)* and scaled movements *(lower part)*

subject practiced all conditions for at least 300 movements. The subjects were instructed to follow the target as accurately as possible in one smooth movement. No explicit instructions about the velocity of the movements were imposed. Emphasis, however, was laid to keep the same pace throughout the experimental runs. The reproducibility, checked by means of phase plane recordings (position vs. velocity), could be met by all subjects. Three paid right handed male subjects were tested.

2.3 Data Analysis

In this section, the different steps in the analysis of the experimental data will be outlined. First of all, the rejection of the initial hypothesis together with the revised hypothesis, as applied in the analysis, will be presented. Next, the describing function model, to parameterize the movements, together with the parameter identification method will be discussed. Based on these two steps, the data processing will be discussed in detail.

2.3.1 Validation of the Working Hypotheses. When, for a given motor task, the variability of the movements would only be due to the variability of the overall velocity of the movements, as stated in the initial hypothesis, then after scaling of the individual movements with respect to the velocity, the variability would diminish. In order to evaluate this hypothesis, the variability of the movements in the phase plane were considered. Firstly, for each experimental run the average contour, together with the variance in the phase plane was calculated. Next, the phase plots of the individual movements were scaled to yield the same maximum velocity for all movements of the same run. Here, the maximum velocity was chosen as a characterization of the overall velocity of the movement. After scaling of the plots, again the average contour and the variance in the phase planes was calculated. Figure 2 gives an example of the phase plane plots, as calculated from 24 forward movements (subject 1, condition 3). In the upper part, the average contour and the standard deviation are plotted. In the lower part, the same contours, calculated after the scaling of the individual movements are presented. As can be seen in this figure, the variability is reduced drastically (decrease in average variance about a factor 8). However, since some variability remains, the variability in the executed movements can not be attributed completely to the variability in the overall velocity. Hence we are forced to to drop the initial hypothesis. The fact, however, that the variance is drastically reduced, allows us to replace this assumption by a less stringent version in which the variability of the overall velocity dominantly contributes to the variability in the movements.

2.3.2 The Describing Function Model. In order to parameterize the movements, necessary for the calculation of the desired movements, a human operator describing function model for goal directed movements was applied. The structure of the model, as given in Fig. 3 is based on the describing function models for random tracking tasks. The model describes the relation between the applied step input $s(t)$ and the actual goal directed movement $x(t)$. The transfer function Hc describes the relation between the actual movement $x(t)$ and the movement $r(t)$ as displayed on the screen. In our case $Hc=1$, hence $x(t)=r(t)$. Apart from the feedback part of the model, which actually describes the movement, the time delay $\tau 1$ accounts for the variability in the response time, whereas the gain factor $K1$ parameterizes the difference between the intended step size and the executed step size. In the analysis these two parameters will not be taken into account.

It should be stressed that the model as presented, only describes the movement from a "black box" perspective; hence no conclusions with respect to the actual control strategy, such as open loop or closed loop, may be deduced from the model structure.

In the complex frequency or Laplace domain the model output $X(s)$ as a response to a unit step $S(s)=1/s$, can be written as:

$$X(s)=\frac{1}{s}\cdot\frac{K_1K_2\exp(-(\tau_1+\tau_2)s)}{s(a_2s^2+a_1s+1)+K_2\exp(-\tau_2 s)}+N'(s), \tag{2}$$

where $N'(s)$, the remnant, equals

$$N'(s)=N(s)\cdot\frac{s}{s(a_2s^2+a_1s+1)+K_2\exp(-\tau_2 s)}. \tag{3}$$

According to Fig. 3, in the time domain the relation between the error $E(s)$ and the output $X(s)$ can be written as

$$x(t)+a1\cdot\dot{x}(t)+a2\cdot\ddot{x}(t)=K2\cdot ei(t-\tau 2)+n(t), \tag{4}$$

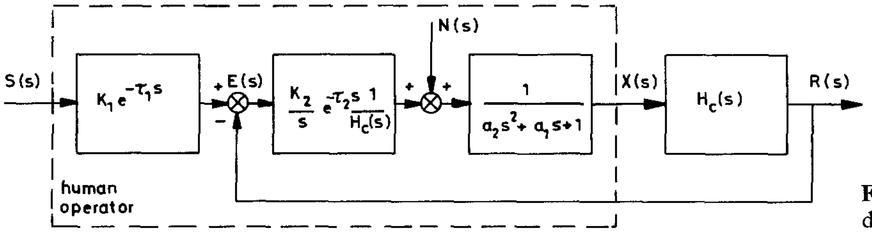

Fig. 3. Describing function model for goal directed movements

where *ei* represents the integrated delayed error input i.e.

$$ei(t-\tau 2)=\int_{t_0}^{t} e(t'-\tau 2)\,dt'. \tag{5}$$

Then the model equation can be defined as

$$\hat{x}(t)=\hat{K}2\cdot ei(t-\hat{\tau}2)-\hat{a}2\cdot\ddot{x}(t)-\hat{a}1\cdot\dot{x}(t), \tag{6}$$

with

$$ei(t)=\int_{t_0}^{t}[\hat{K}1\cdot s(t'-\hat{\tau}1)-x(t')]\,dt'. \tag{7}$$

From (6) and (7) the parameter vector ($\hat{K}1$, $\hat{K}2$, $\hat{\tau}1$, $\hat{\tau}2$, $\hat{a}1$, $\hat{a}2$) was estimated by minimizing the model error ($x(t)-\hat{x}(t)$) according to a mean squared error criterion. Since (6) and (7) are intrinsically non-linear with respect to the time delays $\tau 1$ and $\tau 2$ an adaptive search estimation technique was applied, to estimate these parameters. The parameters $K1$, $K2$, $a1$, and $a2$ could be calculated simultaneously from a linear relation. In this way the recorded movements could be described accurately. Figure 4 gives an example of the measured signals together with the model responses. The magnitude of the model error is typical for all considered movements. The applied model is discussed in detail elsewhere (Sparreboom and van Lunteren, 1984).

2.3.3 Data Processing. In order to study the influences of the different manipulator dynamics on the executed movements, along the lines as pointed out in Sect. 1, the following procedure in the analysis was applied. After preprocessing, in which all movements were tested with respect to the instruction, the average maximum velocity and the variance for each experimental condition, per subject, were calculated. As a check, the manipulator dynamics, as applied during the experiments, were estimated according to (1) from the recorded data. Then for each experimental condition, the parameters of the describing function model were estimated from the recorded movements per subject.

In general, the values of these parameters will vary. This variability can be attributed to the following influences:

– Within each experimental condition due to the differences in the velocities of the executed movements,

– Between the experimental conditions, at equal velocities, due to differences in the shapes of the movements. These migth result from differences in the manipulator dynamics.

According to the hypothesis, as validated in Sect. 2.3.1, the variability within each experimental condition can be reduced by scaling of the movements with respect to the average maximum velocity of each condition. In this way, the desired movement of each experimental condition can be estimated. To investigate the differences between the desired movements and hence to express the possible differences in their shapes, the desired movements of each condition per subject should be scaled to the same maximum velocity. Both the scaling of the movements within each condition and the scaling of the desired movements to the same maximum velocity, are in fact normalizations of the time scales of the movements. These normalizations were performed by operations on the model parameters, using a fundamental property of the Laplace transform.

This property, (Abramowitz and Stegun, 1972) states, that if $X(s)$ is the Laplace transform $L\{x(t)\}$ of the time function $x(t)$ then

$$L\{x(rt)\}=(1/r)\,X(s/r), \tag{8}$$

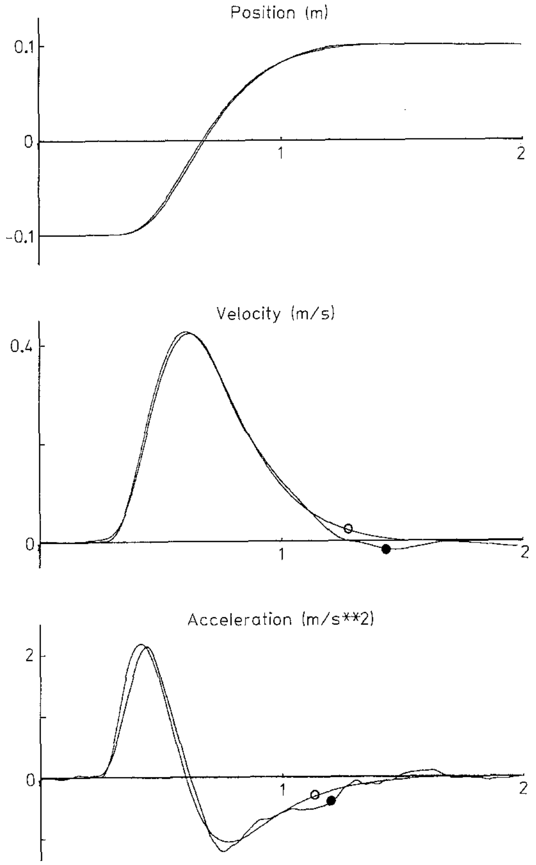

Fig. 4. Recorded (●) and simulated (○) position, velocity and acceleration trajectories. Model parameters: $\tau 1=0.09$ s, $\tau 2=0.22$ s, $K1=1.0$, $K2=1.61$, $a1=0.07$, $a2=0.009$. Magnitude of the model residue: 0.58 * 10 ** − 6

i.e. scaling of a movement in the time domain, where r is the time scale factor, corresponds to the substitution of s/r for s in the Laplacian expression of the movement, combined with a division by the scale factor r. If $r<1$, the movement is slowed down; if $r>1$, the movement is sped up. By inserting (8) in (2), and after rearranging, the parameters can be written in terms of the scale factor r, as presented in Table 2.

After scaling of the movements within each condition the parameters of the desired movements were calculated as the mean and the standard deviation of the scaled movements. To perform the comparison of the different desired movements in the analysis, a distinction has been made between on the one hand

Table 2. The influences of the scaling r in time, expressed in the relevant model parameters of the describing function model

Unscaled	Scaled
parameters	
$\tau 2$	$\tau 2/r$
$K2$	$K2r$
$a1$	$a1/r$
$a2$	$a2/r^2$

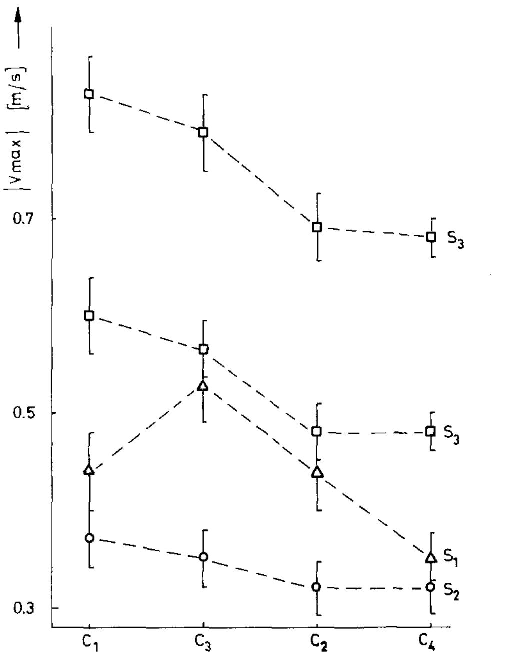

Fig. 5. Absolute averaged maximum velocities and standard deviation vs. experimental conditions for all subjects. Subject *S*3: *upper trace* forward movements; *lower trace* backward movements

the maximum velocity, as a characterisation of the overall velocity, of the desired movements and on the other hand the shape of the movements at equal maximum velocities. The latter was obtained by scaling of the desired movements with respect to the average maximum velocity of the desired movements, for each subject in separate. The parameters of the scaled desired movements together with the variance were calculated according to the above mentioned procedure. Note that the variance, expressed as a fraction of the mean value, remains unchanged under scaling.

3 Results

In order to compare the desired movements of each experimental condition based on the mentioned distinction between the maximum velocities of the desired movements and the shape of these movements, as a first step the averaged maximum velocity and the standard deviation of the two runs of each condition with respect to forward and backward movements were calculated. As no significant differences were found between the forward resp. backward movements of the two runs of each condition, these values could be averaged. Averaging over the maximum velocities of the forward and backward movements of each condition however could only be justified for two subjects; one subject showed a constant, significant difference between forward and backward movements in all experimental conditions. These results, with respect to the 4 experimental conditions are presented in Fig. 5.

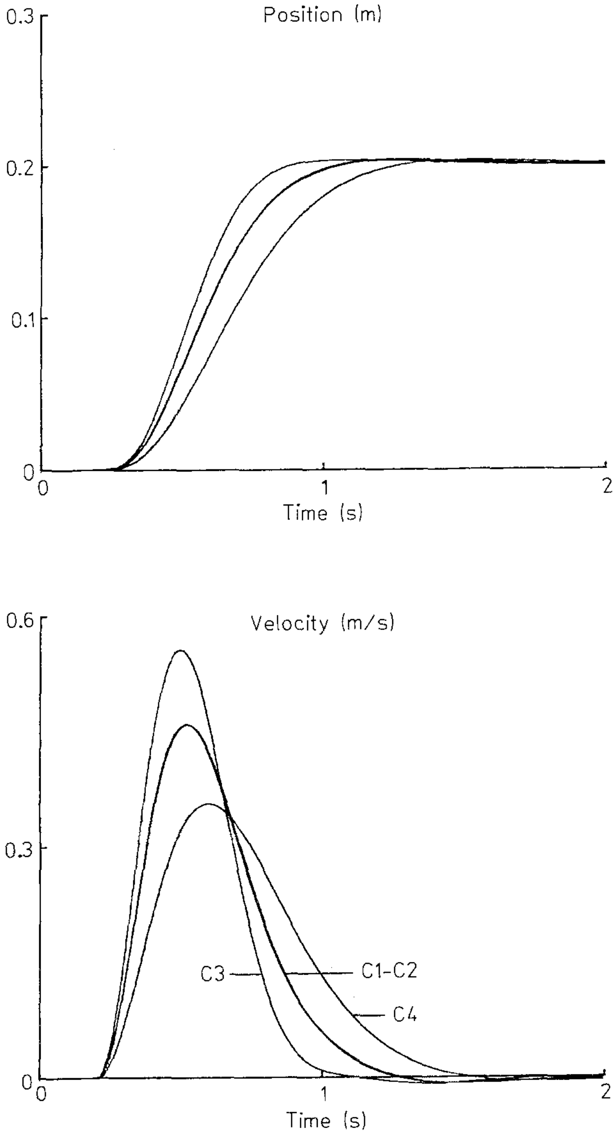

Fig. 6. Simulated desired movements for all experimental conditions, subject *S*1

According to the procedure as described in Sect. 2.3 the desired movements for each condition and for each subject were calculated. Figure 6 depicts the position and the velocity trajectories of the desired movements of subject 1. These were simulated according to (6) and (7) on the basis of the parameters of the desired movements, as calculated according to Sect. 2.3.3. The gain factor $K1$ was set to 1, while the value of the time delay $\tau 1$ was selected to let the movements start at the same moment. Note that already the desired movements of the conditions 1 and 2 coincide. Rescaling of the desired movements with respect to the averaged maximum velocity over all experimental conditions, for each subject in separate, yields the relevant model parameters as given in Table 3. As a typical example,

Table 3. Mean and standard deviation of the model parameters of the desired movements per subject, after scaling with respect to the absolute averaged maximum velocity

Subject	Exp. condition	$\tau 2$ [s]	K2	a1 $\times 10^{-2}$	a2 $\times 10^{-3}$	$\lvert \bar{v}_{max} \rvert$ [m/s]
1	*C*1	0.23	1.58	5.8	10.0	0.44
		(0.04)	(0.15)	(1.0)	(2.1)	
	*C*2	0.23	1.61	6.3	11.2	
		(0.03)	(0.10)	(0.9)	(1.9)	
	*C*3	0.25	1.54	5.6	12.0	
		(0.03)	(0.11)	(0.9)	(2.2)	
	*C*4	0.22	1.64	6.4	9.2	
		(0.03)	(0.10)	(0.9)	(2.0)	
2	*C*1	0.30	1.24	7.4	18.0	0.35
		(0.04)	(0.09)	(1.0)	(3.5)	
	*C*2	0.27	1.33	8.5	14.7	
		(0.04)	(0.10)	(1.0)	(3.5)	
	*C*3	0.28	1.31	8.5	15.0	
		(0.03)	(0.09)	(1.2)	(2.9)	
	*C*4	0.29	1.28	8.1	16.2	
		(0.04)	(0.10)	(1.1)	(3.4)	
3	*C*1	0.27	1.40	3.6	10.5	0.64
		(0.04)	(0.19)	(1.2)	(1.8)	
	*C*2	0.22	1.62	4.8	8.0	
		(0.04)	(0.30)	(0.5)	(1.9)	
	*C*3	0.26	1.44	3.9	9.5	
		(0.03)	(0.20)	(1.0)	(1.6)	
	*C*4	0.26	1.42	4.2	10.2	
		(0.04)	(0.25)	(1.0)	(2.0)	

the simulated trajectories of the scaled desired movements for subject 1 are given in Fig. 7. As can be seen in this figure, the maximum velocities of the four desired movements, which should be equal after scaling, show small differences. These differences are due to the resolution in the time delay $\tau 2$ of the simulation program. In order to investigate the differences between the scaled desired movements for each subject in separate, first of all the differences between the corresponding model parameters were investigated by means of two-tailed tests. Straight forward application of these tests on all corresponding parameters yielded that for subject 1 no significant differences ($p < 0.01$) between the model parameters of the conditions *C*1, *C*2, and *C*4 existed. These results confirm the coinciding scaled desired movements as presented in Fig. 7. For subject 2, no significant differences were found between the conditions *C*2, *C*3, and *C*4, whereas for subject 3 no significant differences between the conditions *C*1, *C*3, and *C*4 existed.

Comparison of the differences in the parameters between the non-significant differing desired movements and the remaining desired movement, for each subject in separate, showed that if the parameters $\tau 2$ differed significantly, then the parameters *K*2 also differed significantly. This result suggested the existence of a dependency between the model parameters, which are not taken into account properly if only the differences between the corresponding model parameters are considered. To include these effects in the analysis of the differences between the desired movements, regression techniques were applied to establish the mutual dependencies of the model parameters. Based on the scaled movements, as used for the calculation of the desired movements, regression equations between the time delay $\tau 2$ and the gain factor *K*2 were calculated for all conditions in separate. After scaling of these equations according to Table 2, with respect to the corresponding desired movement scale factor, the regression equations of the non-significant different conditions were averaged, for each subject in separate. Then the averaged equations were compared with the remaining equation. These results are summerized in Table 4. Analysis of the regression coefficients yielded no significant differences ($p < 0.05$).

Based on both steps in the analysis, it was concluded for each subject in separate, that the scaled desired movements for all conditions coincided. Hence the phasing of the movements is invariant to the different manipulator dynamics.

As the second part of the comparison, the differences between the maximum velocities of the desired

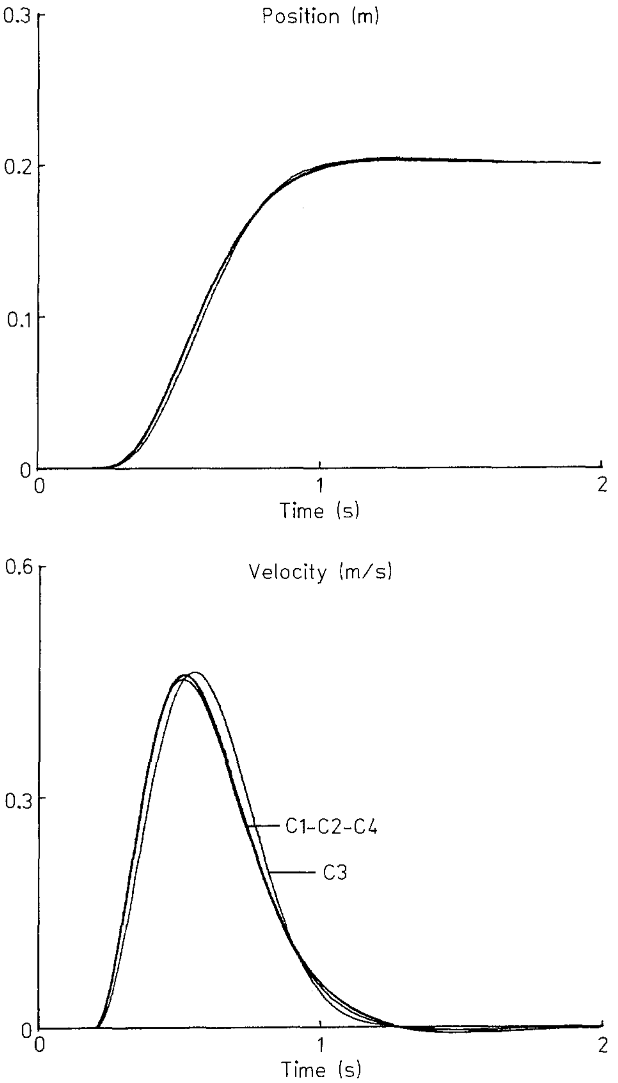

Fig. 7. Simulated scaled desired movements for all experimental conditions, subject $S1$

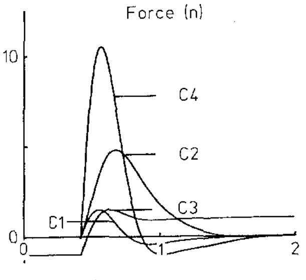

Fig. 8. Simulated force trajectories for all experimental conditions, subject $S1$

Table 4. Regression between $\tau 2$ and $K2$ for each subject in separate

Subject	Exp. condition	$\tau 2$	$\bar{\varrho}$
1	$C1$, $C2$, $C4$	$-0.31\ K2+0.76$	-0.89
	$C3$	$-0.24\ K2+0.65$	-0.92
2	$C2$, $C3$, $C4$	$-0.39\ K2+0.80$	-0.92
	$C1$	$-0.35\ K2+0.75$	-0.91
3	$C1$, $C3$, $C4$	$-0.14\ K2+0.44$	-0.84
	$C2$	$-0.13\ K2+0.44$	-0.92

movements with respect to the different manipulator dynamics were analysed. As, according to the instructions on the motor task, the velocity of the movements could be freely chosen by the subjects, only the changes of the average maximum velocity of each condition relative to the mean value of the average maximum velocity over all four experimental conditions per subject were considered. After the calculation of the average relative changes over all subjects for each condition in separate, the differences in the resulting relative changes were tested by means of a two-tailed test. These tests yielded a significant difference ($p < 0.05$) between on the one hand the relative changes of the maximum velocities in the conditions $C1$ and $C3$ and on the other hand the changes in $C2$ and $C4$. The difference between $C1$ and $C3$, respectively, $C2$ and $C4$, was not significant. Taking the signs of the relative changes into account, it can be concluded, that the manipulator dynamics, as applied in the experimental conditions $C2$ and $C4$ tend to slacken the executed movements, whereas the dynamics in the conditions $C1$ and $C3$ tend to quicker the movements.

Starting from the scaled movements, using (1), the exerted force trajectory of each experimental condition, based on the estimated manipulator parameters, was simulated. As an example, Fig. 8 depicts these trajectories for subject 1. The influences of both the values of the manipulator parameters and the order of the dynamics are clearly expressed. Taking into account that the scaled desired movements coincide, it can be concluded that the exerted force trajectories are fully adapted to the different manipulator dynamics, i.e. the differences in the manipulator dynamics are fully compensated. Comparison of the exerted force trajectories, as given in Fig. 8, and the results on the relation between the manipulator dynamics and the relative changes in the maximum velocities of the desired movements, indicate a dependency between the maximum exerted force and the relative changes in the maximum velocity: Higher exerted forces correspond to a decrease in the maximum velocity. The lack of data, however, does not permit to study this dependency in more detail.

In conclusion, the results of the analysis as presented, can be summerized as follows: The phasing of the goal directed movements, executed by means of a manipulator with various dynamics, are invariant under variation of the manipulator dynamics. These dynamics however tend to influence the velocity of the execution of the movements.

4 Discussion

In order to establish the influences of different loadings on goal directed movements, executed movements, considered as realisations of a stochastic process, were characterised by means of the desired movement concept, a description of the expectation and the variance of the process. The resulting desired movements were compared both with respect to the maximum velocity and the shape of the movement.

As only some slight dependencies between the relative differences in the maximum velocities and the different loadings could be established, it can be argued, that the velocity of the executed movement is a parameter that can be adjusted freely over certain ranges. For given motor tasks, the results indicate, that these ranges seem to be upper bounded by the dynamics of the manipulator by which the movements are executed. Within these ranges, the relative changes may be attributed to the strategy of the subject as adopted during the execution of the movements. Figure 5 shows that these strategies might be the same for subject 2 and 3, although the absolute values differ, for subject 3 even between forward and backward movements, but clearly differs from subject 1.

Whereas the force trajectories for the considered loads clearly differ, as shown in Fig. 8, the invariance in the phasing of the movements implies that the different loads are fully compensated.

These results extend the findings with respect to the invariance in the phasing at different movement times (Armstrong, 1970; Soechting and Lacquaniti, 1981), to the invariance in the phasing at different loads.

Both results, the adjustable velocity and the invariance in the phasing are in agreement with the current viewpoints on generalized motor programs, as the abstract structure that governs motor responses (Schmidt, 1980). The overall velocity is a mutable parameter, a variant feature of the motor program, whereas the invariance in the phasing, or expressed differently, the invariant relative timing of the movement, is an invariant element in the motor program (Summer, 1975; Shapiro et al., 1981).

From a control point of view, the nature of the compensation can only be interpreted in the context of the control of the executed movement.

According to the instructions as given to the subject, we may assume that the movements are planned in terms of the position, either by some form of preprogramming of the position trajectory (Morasso, 1981; Abend et al., 1982), generalized motor programs (Schmidt, 1980), trace concept (Vincken, 1983) or final equilibrium position specification (Feldman, 1974; Kelso et al., 1980).

In the control of the manipulator to execute a planned position trajectory, position control and force control can be distinguished as extreme strategies. In the former, the intended position trajectory of the manipulator is specified whereas in the latter the forces to be exerted are prescribed.

With respect to the adaptation or compensation of the different loads the position control view only implicitely accounts for the adaptation. It however requires an adequate position feedback to accomplish the compensation of the loads, during the execution of the movements (Soechting and Lacquaniti, 1981). In the force control view, adaptation to different loads can only be achieved if, in some way, the required force trajectories are redetermined with respect to the different loads. Various solutions as plausible biological mechanisms, to accomplish the calculation of the inverse kinematics and dynamics have been proposed (Albus, 1975; Raibert, 1978).

Another mechanism to accomodate the compensation has been suggested by Hogan (1980). It involves the regulation of the intrinsic mechanical stiffness of the muscles. Hence the adaptation can be achieved by tuning the muscle impedance, subjects own mechanical system parameters, to the dynamics of the load. Moreover, when the muscle impedance is thus tuned to obtain the same resulting impedance for different loads, this might also explain the invariance in the phasing of the movements as pointed out in this paper. However, while an attractive hypothesis, the validity for human arm movements has not yet been determined.

Although these concepts tend to provide more or less excluding possibilities to interprete the observed compensation of the different manipulator dynamics, the results presented, do not allow further inferences with respect to the credibility of the mentioned viewpoints. As the subjects practiced all loads thoroughly, this research in fact only focussed on the steady state situation, as reached after adaptation. Hence, the role of the peripheral information, as used during the adaptation of the control of the movements to the changed manipulator dynamics, might be diminished. However, these viewpoints together with the presented results and the concepts as applied in the analysis, may serve in an investigation of the adaptation to changes in the loads.

Finally, it should be noted, that we did not focus on the role of the visual information in the invariance in the phasing of the movements and the adaptation to different loads. Some preliminary experiments however indicate that the absence of visual information only affects the final position of the movements and hence increases the variability in the distance scaling of the executed movements. However, when the movements are scaled with respect to the same final position by means of the gain factor $K1$, these data seem to match the reported results.

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