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Factors Influencing the Force Control During Precision Grip

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Summary. A small object was gripped between the tips of the index finger and thumb and held stationary in space. Its weight and surface structure could be changed between consecutive lifting trials, without changing its visual appearance. The *grip force* and the *vertical lifting force* acting on the object, as well as the *vertical position* of the object were continuously recorded. Likewise, the minimal grip force necessary to prevent slipping, was measured. The difference between this minimal force and the employed grip force, was defined as the *safety margin* to prevent slipping.

It was found that the applied grip force was critically balanced to optimize the motor behaviour so that slipping between the skin and the gripped object did not occur and the grip force did not reach exeedingly high values. To achieve this motor control, the nervous system relied on a mechanism that measured the *frictional condition* between the surface structure of the object and the fingers. Experiments with local anaesthesia indicated that this mechanism used information from receptors in the fingers, most likely skin mechanoreceptors. In addition to friction, the control of the grip force was heavily influenced by the *weight* of the object and by a *safety margin factor* related to the individual subject. The frictional conditions during the previous trial could also, to some extent, influence the grip force.

Key words: Precision grip – Human hand – Motor control – Sensory input – Cutaneous mechanoreceptors

Introduction

One of the most important features of the hand is its prehensile capacity, i.e. the ability to grasp and hold objects. Small objects are handled between the tips of the fingers and thumb in a precision grip that can be very accurately controlled (cf. Napier 1956). This grip serves as a basis for further precision handling which may involve rotation of the object about one of its own axes or transposition of the object in space. Evidently, in this kind of refined motor behaviour there is a close interplay between sensory mechanism related to explorative functions of the fingers and motor mechanism controlling the muscles of the hand. Indeed, lesions of the primate pyramidal tract as well as the dorsal columns, i.e. one major descending and one major ascending pathway who phylogentically envolved in parallel with the development of the capabilities of the distal extremities, lead to severe impairment of the precision grip (Lawrence and Kuypers 1968; Vierck 1978).

The problem of the present study was to quantitatively examine to what extent the grip force is adjusted to mechanical properties of objects manipulated between the index finger and thumb. In the absence of visual cues, such adaptive capacities may depend on somatosensory information arising from mechanoreceptors in the finger.

While there are an almost infinite number of phases in precision manipulating in general, it was necessary to find a motor task which required changes in grip force but still be amenable to quantitative studies. Our approach was to measure the grip force and the vertical lifting force when small objects were held stationary in the air between the tips of the index finger and thumb (pinch grip). During this task, to maintain stability and to prevent accidental slipping, the grip force has to exceed the minimum value which is determined by (1) the friction between the object and the skin and (2) the vertical lifting force. It will be shown that at least four different factors, including these two, could influence the applied grip force. Moreover, an appropriate grip

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force control was dependent on activity in afferents terminating in the fingers.

Preliminary reports of the present results have been given (Westling and Johansson 1980; Johansson and Westling 1981).

Material and Methods

Sixteen right-handed subjects (4 females and 12 males, 15–49 years old) participated in the present study. They were completely naive with regard to its purpose. Before the experiments (5–10 min) the subjects were asked to wash their hands with soap and water. During the experiments the subjects sat in an ordinary chair with their right upper arm parallel to the trunk, and with their unsupported forearm extending anteriorly. From this position an object on a table was grasped between the index finger and thumb of the right hand and lifted (Fig. 1). The lifting movement took place mainly as a flexion of the elbow joint. For timing purposes, a large illuminated clock with a second-hand was placed in front of the subject. The lighting of the room was adequate for finding the object but not for visual discrimination of the structures of the touched surface (see below).

The experimental apparatus is shown in Fig. 1. The surfaces touched by the subjects were two easily exchangeable discs mounted in planes. The object could be loaded with different weights without changing its visual appearance. The *grip force* and the vertical lifting force denoted as the *load force* was continuously measured, as well as the vertical position of the object.

The *instructions* given to the subjects were limited to a demonstration lifting carried out by the experimenter and the following verbal instructions: "Lift the object with the index finger and thumb to about two cm above the table. Keep it at about this position for 15 s (in some lifting series 10 s). Then, slowly move the index finger and thumb apart until you drop the object. For help with the timing, you have a clock in front of you. For each lifting I will tell you when to start". In some of the experiments the subjects were asked to replace the object on the table in an ordinary fashion rather than dropping it (cf. Fig. 2A). Thus, the subjects were not instructed to pay attention to the grip force but to the timing and to the positioning of the object in space. The whole sequence, from the moment the object was initially touched until the subject let go of the object, will, in the following, be denoted as a *trial*. The procedure involving the dropping of the object was carried out in order to measure the minimal grip force required to prevent slippage. This force was denoted as the *slip force*, and was measured at the moment when the object just began to slip (Fig. 2B), which could be defined either from the position signal or from the sudden decrease in the load force. The interval between consecutive trials was 10–15 s.

The *structure of the touched surface* could be altered between trials by changing the touched discs (Fig. 1). Three pairs of discs, covered by *sandpaper* (no. 320), *suede* (type of leather) and a finely textured *silk*, respectively, were used. These surface structures were chosen on the basis of their different frictional properties in relation to the skin. The coefficient of static friction for the three surface structures was calculated from the slip force measurements. Its average value (10 subjects) for sandpaper, suede and silk was 1.21, 0.68 and 0.35, respectively. The surface structures reasonably followed the law of friction according to Amontons (Bowden and Tabor 1973; Comaish and Bottoms 1971), i.e. the coefficients of friction did not vary appreciably with the magnitude of the load force for load force magnitudes greater than 1 N (Newton) (cf. Results). However, for suede, and particularly silk, there was a great variability in the coefficient of friction between subjects whereas it was about constant for sandpaper. The subject exhibiting the smallest difference in friction between the three surface structures had an average ratio between the coefficients obtained for sandpaper and suede of 1.6 and between sandpaper and silk of 1.9 whereas the corresponding ratios for the subject with the largest difference were 2.6 and 4.6, respectively. Moreover, the coefficient of friction could vary (up to about +/- 20% of the average value) between different trials carried out with the same surface structure and by the same subject. One factor which may have accounted for this interindividual variability was possible differences in the sweating rates.

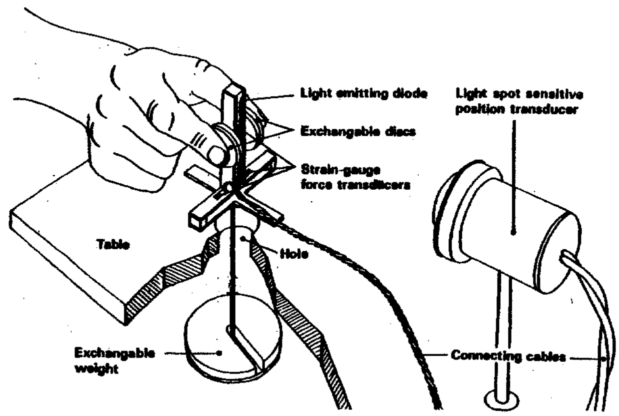

Fig. 1. Schematic drawing of the apparatus. The surfaces touched by the subject were two easily exchangeable discs (diameter: 30 mm), mounted in two parallel planes at a distance of 30 mm. They were attached to each side of a pair of vertical metal rods, which lower ends were attached close to the center of a horizontal metal cross supporting the object on the table. A 25 cm long thin metal rod attached in the center of the cross passed through a hole (diameter: 30 mm) in the table. Its lower end was loaded with various weights, shielded from the subject's view by the table. The object was equipped with two sets of calibrated strain gauges (DC – 120 Hz) to measure the grip force and the vertical load force. The vertical position of the object was measured (DC – 1.5 kHz) with a light-position sensitive photoresistor (United Detector Technology, SC/28) mounted in a camera sensing the position of an infra-red light emitting diode fixed to the object

More than 1000 trials gathered from different types of lifting series were studied. Two of the series, each run on 10 subjects, included 16 consecutive trials terminated by measurements of the slip force (cf. Fig. 2B). In one series, the surface structure was constant whereas the weight of the object was pseudorandomly varied between the trials. Three weights were used: 200 g, 400 g, and 800 g. In the other series the weight of the object was constant, whereas the three different surface structures were presented in a pseudorandom sequence. The pseudorandom series were designed in order to detect possible influences of weight and surface structure of the object in the previous trial on the behavior in the subsequent trial. The same kind of series were also run, without slip force determinations (cf. Fig. 2A). To obtain an estimate of the slip forces in these series, extra trials with the slipping procedure were added at the end. Differences in the motor behavior during the two conditions were not observed (except in the end of the trials). In addition, four of the subjects ran several other lifting series with the three different surface structures and with different weights (100–1,000 g, varied in steps of 100 g between trials).

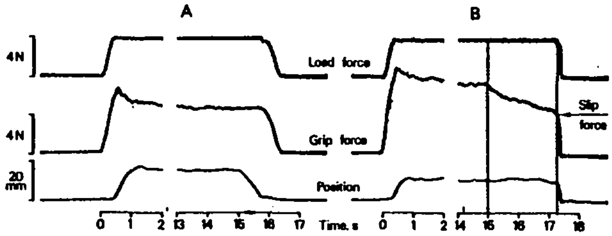

Fig. 2. Load force, grip force and vertical position shown as a function of time for two different kinds of lifting trials. **A** sample trial with lifting and replacing of the object in an ordinary manner. **B** sample trial with dropping of the object due to a slow voluntary spacing of the fingers at the end of the trial. Left vertical line indicates the start of spacing. The grip force value at the moment the object slipped (*right vertical line*) was denoted slip force (*arrow*). Note the interrupted time scales

Local anaesthesia of the index finger and thumb was performed on three subjects by blocking the four digital nerves at the proximal phalanges (5 mg Marcain/digit). Before and during anaesthesia, these subjects carried out the similar kinds of lifting series as described above.

Results

Some general characteristics of the lifting trials appear in Fig. 2. Before the object began to move, the grip force and the load force increased in parallel. After the moment the load force overcame the force of gravity acting on the object, the object moved, and the grip force and the load forces continued to increase for a short period of time until reaching peak

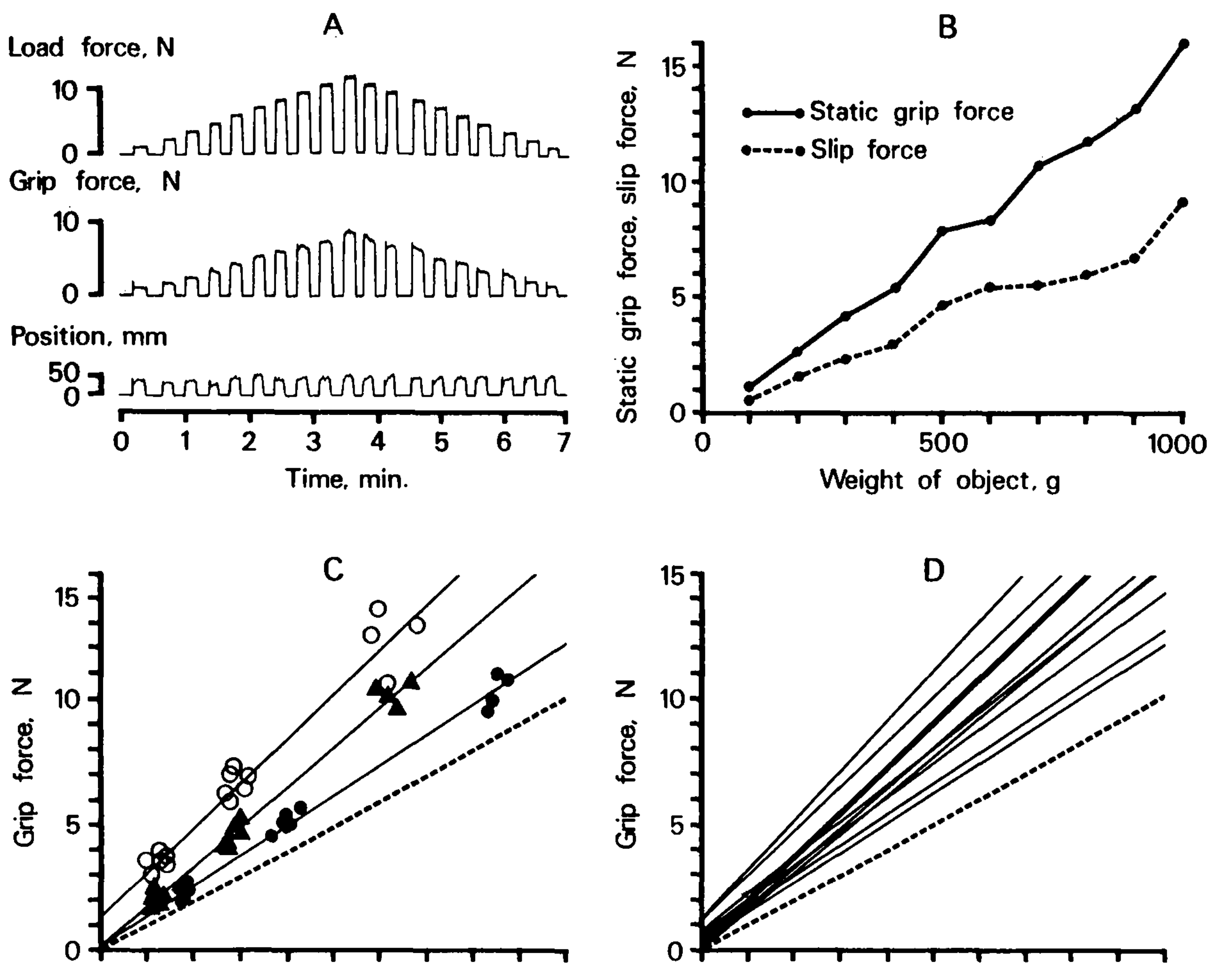

Fig. 3. Adjustments of the static grip force with weight changes. **A**, nineteen consecutive trials between which the weight was varied in steps of 100 g. Load force, grip force and vertical position as a function of time. **B**, Grip force (solid curve) and slip force (segmented curve) in relation to the weight of the object (single subject). Data points refer to 10 consecutive trials with the weight increased in steps of 100 g in between. **C**, and **D**, relationship between static grip force and slip force obtained in lifting series with pseudorandom changes of the weight of the object between 16 consecutive trials. Three weights were used: 200 g, 400 g, and 800 g. Segmented lines indicate minimal grip forces required to prevent slipping. **C**, data points and linear regression lines referring to three subjects represented by different symbols respectively. **D**, linear regression lines for 10 subjects including those in **C**. **A**, **B**, **C** and **D**, surface structure constant using suede

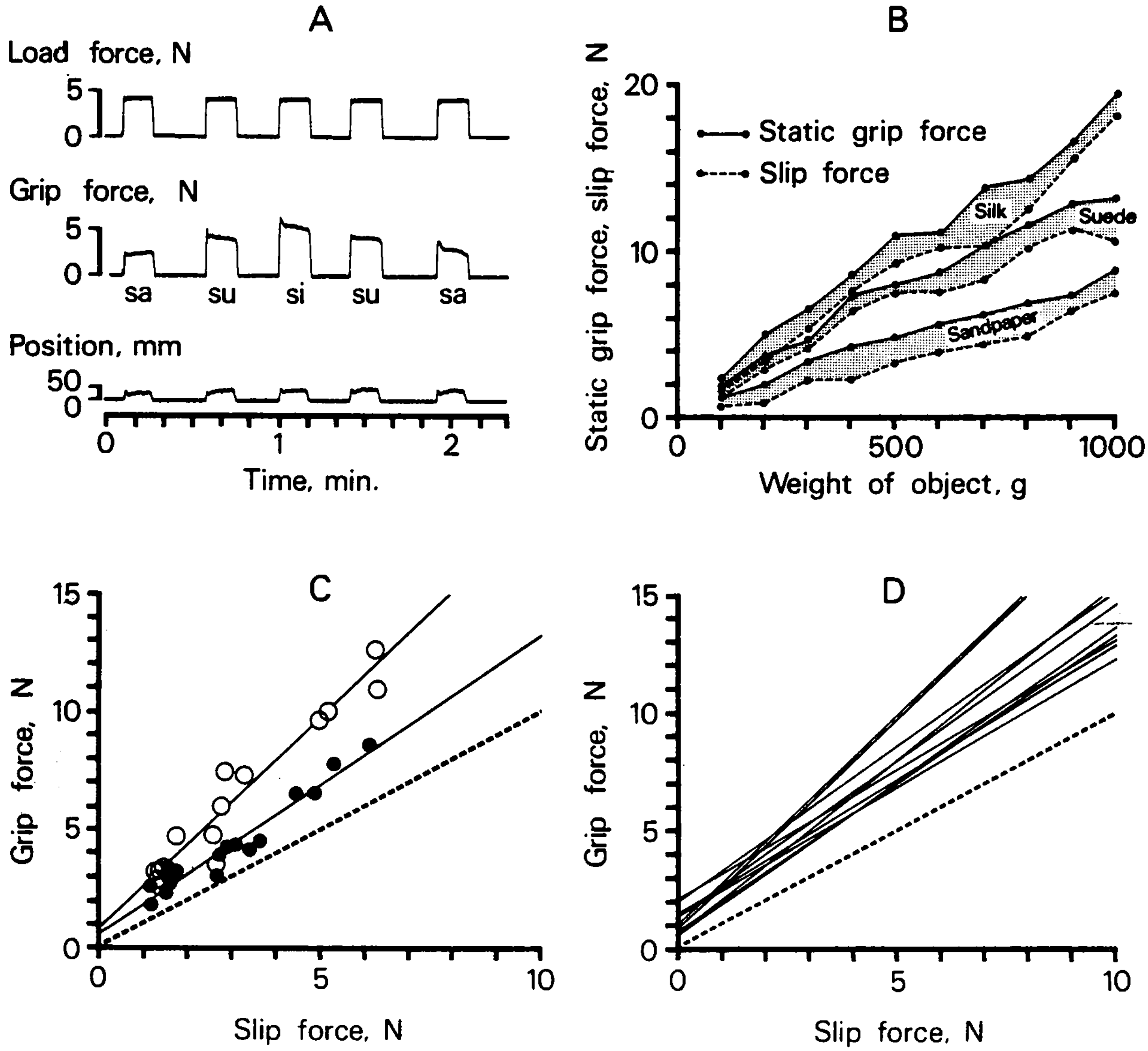

Fig. 4. Adjustments of the static grip force to changes of surface structure. **A**, 5 consecutive sample trials with sandpaper (*sa*), suede (*su*), silk (*si*), suede and sandpaper, respectively. Load and grip forces, as well as vertical position shown as a function of time. Weight constant at 400 g. **B**, relationship between weight of object and grip forces (solid curves) and slip forces (segmented curves) for three consecutive lifting series with sandpaper, suede and silk, respectively (single subject). Each series consisted of 10 consecutive trials with the weight increased in 100 g steps for each succeeding trial. Dashed areas illustrate safety margins. **C**, and **D**, relationship between grip and slip forces in lifting series with pseudorandom changes of surface structure between 16 consecutive trials. Segmented lines as in Figs. 4**A** and **B**. **C**, data points and linear regression lines referring to two subjects, represented by different symbols. For the single subject, the four symbols with the highest slip forces refer to trials with silk whereas the next six symbols refer to suede. The six symbols at the lowest slip forces refer to sandpaper. **D**, linear regression lines referring to 10 subjects including those in **C**. **A**, **C** and **D**, weight constant at 400 g

values. About 1 s later the forces stabilized at approximately constant levels for most trials, and a *static phase* was entered during which the object was held approximately stationary in space. After the replacement of the object there was a parallel decrease in grip force and load force until the object was released (Fig. 2A). The grip force value at 8 s after the onset of the grip force increase was arbitairly choosen as a measurement of the *static grip force*.

Relation Between Static Grip Force and Weight

The influences of the weight on the static grip force were studied in lifting series with the surface structure constant. As illustrated in Fig. 3A, which shows the a lifting series in which the weight was varied in an ascending-descending order, the heavier the weight the larger the grip force. The static grip force was approximately proportional to the weight of the object, i.e. to the static load force (cf. solid curve in

Fig. 3B). Likewise, the relationship between the load force and the slip force, i.e. the minimal grip force required to prevent slipping, was approximately proportionate (cf. segmented curve in Fig. 3B), with a ratio between the two forces determined by the coefficient of friction.

A comparison between subjects with regard to the employed grip forces indicated that there could be large differences although the corresponding slip forces were about the same. Thus, the *safety margin* for the prevention of slipping, defined as the difference between the grip forces and the slip forces could vary between the subjects. This is illustrated in Fig. 3C and D which show the relationship between the static grip forces and the slip forces for different subjects. The complete data from three subjects are shown in Fig. 3C, in which each trial is indicated by a symbol. Due to the three discrete weights of the object (200 g, 400 g and 800 g), the symbols tended to cluster in three main groups along the slip force axis. The scatter of the slip force within these groups was accounted for by variations of the coefficient of friction between subjects as well as between consecutive trials for the individual subjects.

The relationship between the two forces could fairly well be described by linear regression, with an intercept close to zero for most subjects. The regression lines for 10 subjects are shown in Fig. 3D (r = 0.931 to 0.995 with a mean r-value of 0.975). Thus, the vertical distances between the segmented line (grip force eq. slip force) and the solid lines referring to the subjects, represent the safety margin. For most subjects it increased with the slip force and constituted an approximately constant fraction of the employed grip force, i.e. the *relative safety margin* defined as the safety margin in percent of the grip force value was about constant. For subjects with an extremely small safety margin, it was rather a constant absolute value than a constant fraction of the grip force (cf. Figs. 3D and 4B).

Relation Between Static Grip Force and Surface Structure

Changes of the surface structure between trials gave rise to a marked variation in the grip forces although the weight of the objects was kept constant (Fig. 4A). Figure 4B shows the static grip force (solid curves) and the slip force (segmented curves) as a function of weight and surface structure. In accordance with the results described in the previous section, there was an approximately linear relation between the static grip force and the weight of the object. However, the slope of this relation was different for the three

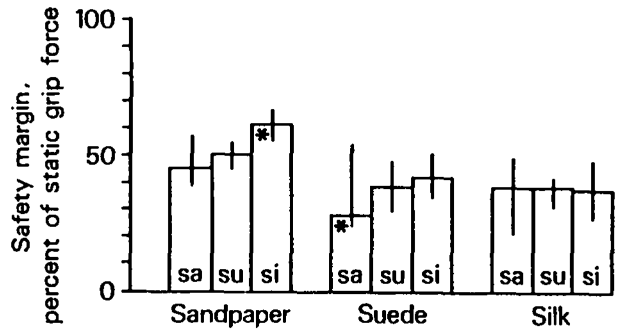

Fig. 5. Influences of the surface structure of the object in the previous trial on the employed safety margin. The three groups of columns refer to trials with the three different surface structures as indicated. The three columns in each group labelled *sa*, *su* and *si* refer to sandpaper, suede and silk as surface structure in the previous trials, respectively. Column heights and bars give medians, and 25th and 75th percentiles. Stars indicate statistically significant differences between the trials represented by the starred columns and the next following trials carried out without change of surface structure ($P < 0.02$, Wilcoxons paried test). Weight of object constant at 400 g. Data based on lifting series with pseudorandom changes of surface structure between consecutive trials (160 trials, 10 subjects)

surface structures, being higher the more slippery the surface structure. A comparison between the grip force and slip force curves revealed that this change in slope was compatible with an adjustment of the grip force to the frictional demands, i.e. this adjustment served to maintain an adequate safety margin (dashed areas in the graph). The subject in Fig. 4B and in Fig. 3B represented two extremes with regard to the size of the safety margin.

Figure 4C and D show the capacity of the grip force adjustment to friction for 10 different subjects. In Fig. 4C the static grip force is shown as a function of the slip force for two of the subjects, whose trials are indicated with different symbols. It may be pointet out that the slip force variation between trials was accounted for by frictional differences as the weight of the object was constant. Again, it is clear that the static grip force was adjusted to the slip force. The obvious adjustment of the grip force with larger variations in slip force between trials with the same surface structure indicated that it was the friction *per se* rather than the surface texture that accounted for the adjustment. As for the data described in Fig. 3C and D, concerning weight changes, the relationship between the two forces could fairly well be described by linear regression. The obtained regression lines for all of the 10 subjects are shown in Fig. 4D (r = 0.843 to 0.970, with a mean r-value of 0.926). The safety margins were similar to those encountered in series with weight changes (cf. Figs. 3D and 4D). Thus, it

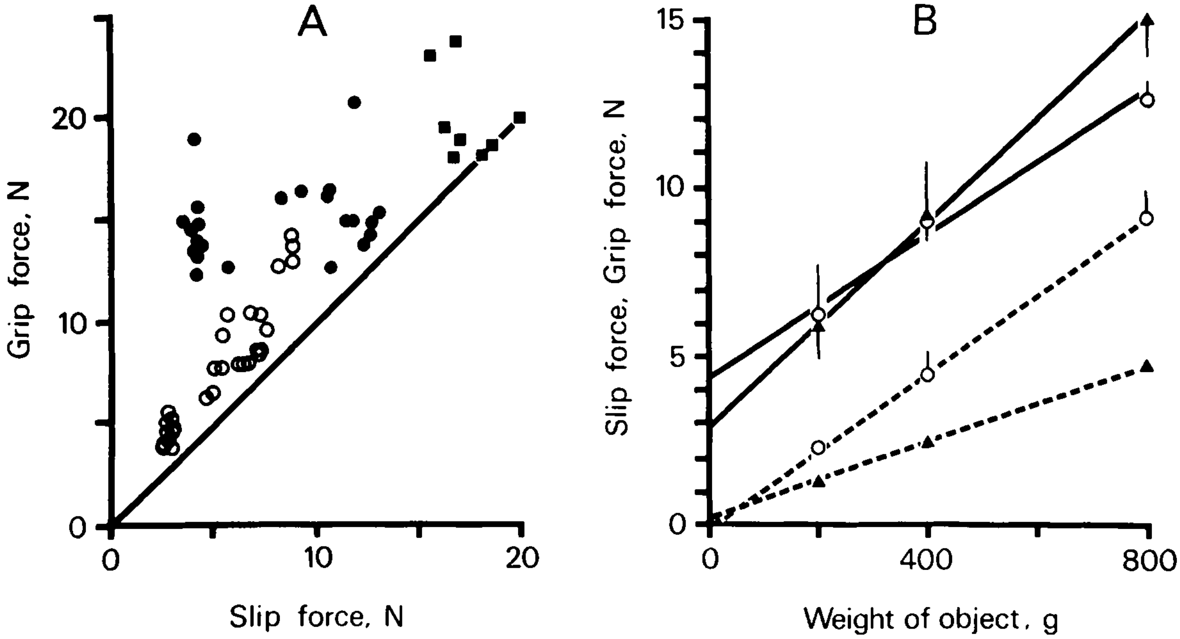

Fig. 6. Static grip forces during local anaesthetic block of the digital nerves of the index finger and thumb (single subject). **A**, relationship between grip and slip forces before (*open symbols*, 32 trials) and during (*filled symbols*, 32 trials) anaesthesia. *Filled circles* refer to trials with sandpaper and suede whereas squares refer to trials with silk. *Solid line* indicates the minimal grip forces necessary to prevent slipping. Weight of object was constant at 800 g, implying that the slip force variation between trials was accounted for solely by frictional changes. The higher slip forces during anaesthesia compaired to the normal condition was most likely caused by less sweating. **B**, relationship between weight of object and grip forces (*solid lines*) and slip forces (*segmented lines*) obtained in two lifting series with suede (*circles*) and sandpaper (*triangles*) as surface structure during anaesthesia. Both series contained 32 trials with pseudorandom changes of the weight (200 g, 400 g and 800 g) in between. Symbols, bars and lines indicate means, standard deviations (unilaterally indicated) and linear regression lines respectively

increased with increasing slip force for most subjects and could vary between subjects. However, the intercepts of the regression lines tended to be slightly larger than with weight changes. The main reason for this was that the relative safety margin tended to be greater for sandpaper than for the other two surface structures (cf. Fig. 5). A comparison between the r-values for the lifting series with weight and surface structure changes, respectively, indicated a larger data scatter in the latter series. This scatter was partly due to influences of the surface structure of the object in the previous trial.

Influences of the Previous Trial

There were no obvious influences of the weight of the object in the previous trial on the static grip force. In contrast, the surface structure of the previous trial could influence this force. This is illustrated in Fig. 5 in terms of influences on the relative safety margins. The three groups of columns refer to trials with sandpaper, suede and silk, respectively, and the columns in each group refer to the surface structure of the previous trial. Considering trials with sandpaper, the safety margin appeared to increase if the preceding trials were with suede and silk, i.e. more slippery surface structures, compared to previous trials with sandpaper. The influence of silk, i.e. the most slippery structure, was greatest and was statistically significant. As to trials with suede, silk in the previous trial tended to increase the safety margin compared to previous trials with suede whereas the reverse was the case for sandpaper. Only the influence of sandpaper was statistically significant. As to trials with silk, there were no obvious influences from the surface structure of the previous trials. It may be noted that the influences of the previous trials appeared to be small compared to the adjustment of the grip force to the current structure (cf. Fig. 4C).

Local Anaesthesia of Index Finger and Thumb

The appropriate adjustment of the grip force to changes in surface structure was lost when the digital nerves were blocked. The employed grip force was unrelated to the slip force. For one subject (represented in Fig. 6), the grip force was strong enough to avoid slipping between the skin and the object only for trials with sandpaper or suede (filled circles). In trials with silk, the fingers slipped over the object which remained motionless on the table. The subject was then asked to repeatedly try until successful. Usually, after 2 to 4 trials during which the subject consciously increased the grip force, the object was successfully lifted. The successful trials with silk are represented by filled squares in Fig. 6A. With silk, it also occurred that the object was dropped during the static phase of the trial. Most of the symbols located at the line in Fig. 6A refer to such trials. For the remaining subjects, the grip force was high enough to prevent slipping even in trials with silk.

The capacity of anaesthetized subjects to adjust the grip force to weight is illustrated in Fig. 6B, for lifting series with suede (circles) and sandpaper (triangles), respectively. The solid lines show the static grip forces and the segmented lines the corresponding slip forces. It can be seen that there was an adjustment of the grip force to weight changes, although the employed grip forces were about the same at the two surface structures. In addition to the lack of adjustments to frictional changes during anaesthesia there was a higher intercept of the linear relationship between grip force and weight (cf. Figs. 3B and 4B).

Discussion

The present results show that the employed grip force when holding a small object stationary in space was critically balanced in the sense that neither accidental slipping between the skin and the object occurred, nor did the grip force reach exceedingly high values. Too firm a grip may lead to muscle fatigue and/or destruction of a fragile object as well as causing injuries to the hand. It may also interfere with further manipulative activity superimposed on the basic grip. There were primarily three factors influencing the magnitude of the employed grip force: the weight of the object, the friction between the skin and the object, and a safety margin factor related to the individual. In addition, the frictional conditions during previous trials could, to some extent, influence the grip force. To achieve this motor response, there must exist a *physiological mechanism* providing the central nervous system with information related to the friction between a gripped object and the glabrous skin of the fingers. The importance of the capacity to adjust the grip force with variation in friction is obvious since the friction may vary widely between different materials, and for the same material under different conditions (cf. Comaish and Bottoms 1971; Bowden and Tabor 1973; Wilkes et al. 1973).

Whatever the details of this mechanism, a reasonable hypothesis would be that *mechanoreceptors in the skin* of the fingers are involved. The effects of blocking of the digital nerves supported this hypothesis. The glabrous skin of the human hand, and particulary the finger tips, has an extremly high density of mechanoreceptors, which can accurately signal a variety of mechanical events (for ref. see Johansson and Vallbo 1983). It is well known that signals in afferents terminating in the fingers play an important role in precision motor control. For instance, it is common experience that precision manipulation is heavily disturbed when the fingers are chilled as well as during pathological impairments of the skin sensibility. There are several recent observations in man which may provide some clues about the functional role of afferents in the fingers during manipulation (Marsden et al. 1977; McCloskey and Gandevia 1978; Torebjörk et al. 1978; Garnett and Stephens 1981). These studies all emphasize the input from skin and joint afferents in the fingers as having a general facilitatory effect on motor commands accounting for certain finger movements (mainly flexion). However, the present findings suggest that the same group of afferents further can provide very specific information, which is essential for the adaption of the motor performance to its environmental goals.

The fact that anaesthesia of the fingers abolished the capacity to adjust the grip force with friction, but not adjustments with the weight of the object, suggests that the control of the grip force relied on two different mechanisms. One would be concerned with the adjustment to friction between the skin and the object and would operate on the basis of afferent information from receptors in the fingers. In the absence of signals from these receptors, as during anaesthesia, the grip forces appeared to be set close to values matching the most slippery frictional condition during the lifting series, i.e. the subjects could manage to pick up the loads but with a tendency to fail at the most slippery surface structures. The other mechanism would account for the relationship between the grip force and the weight of the object, i.e. the load force, without requiring activity in mechanoreceptors of the fingers. The *two proposed mechanisms* may be related to anatomically differential motor pathways: corticospinal and laterally descending brain stem pathways; and medially descending brain stem pathways, respectively. The corticospinal system, which represents a highly differentiated system, is supposed to be closely interrelated with sensory functions and include direct corticomotorneuronal connections with an emphasis on distal extremity muscles (Kuypers 1981). It may be of relevance in this context that the primate motor cortex receives detailed information over very rapid pathways from mechanoreceptors in the glabrous skin of the hand (Lemon 1981). The medially descending brain stem pathways, on the other hand, are considered to be more concerned with posture and synergistic whole-limb movements (Kuypers 1981).

The influences of the surface structure of the object in the preceding trial must be regarded as an after-effect or a memory trace related to the frictional conditions. This phenomenon may be of value in anticipating the frictional conditions while gripping objects during daily life. However, during the present experiments, it seemed to interfere with the frictional appreciation during the current trial. Strong evidence that this after-effect was related to friction rather than to the magnitude of the static grip force *per se* was the absence of influences of previous trials in lifting series involving changes of the weight of the object. Therefore its mechanism seems to be different from that accounting for the "postural after-contractions" as discussed by Granit (1972).

There was a large variation in safety margin between subjects, i.e. some subjects tended to grip much firmer than others at a given slip force. We believe that most of this variation was related to parameters within the central nervous system. Interestingly, it appeared that subjects with greatest manual dexterity employed the smallest safety margins. Likewise, it tended to increase during periods of general motor activity occurring in parallel with the static phase of the trial, e.g. if the subject with the free hand rubbed the skin in the face due to localized itching.

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