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RESEARCH ARTICLE

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The effects of muscimol inactivation of small regions of motor and somatosensory cortex on independent finger movements and force control in the precision grip

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Abstract This study investigated the effects of inactivating small regions of the primary somatosensory (SI) and motor (MI) cortex on the control of finger forces in a precision grip. A monkey was trained to grasp and lift a computer-controlled object between the thumb and index finger and to hold it stationary within a narrow position window for 2 s. The grip force applied perpendicular to the object surface, the lifting or load force applied tangentially in the vertical direction, and the vertical displacement were sampled at 100 Hz. Also, the ability of the monkey to extract small pieces of food from narrow wells of a Klüver board was analyzed from video-tape. Preliminary single-unit recordings and microstimulation studies were used to map the extent of the thumb and index-finger representation within SI and MI. Two local injections of 1 µl each (5 µg/µl) of the $GABA_A$-agonist muscimol were used to inactivate the thumb and index region of either the pre- or post-central gyrus. The precision grip was differently affected by muscimol injection into either SI or MI. MI injections produced a deficit in the monkey's ability to perform independent finger movements and a general weakness in the finger muscles. Whole-hand grasping movements were inappropriately performed in an attempt to grasp either the instrumented object or morsels of food. Although the effect seemed strongest on intrinsic hand muscles, a clear deficit in digit extension was also noted. As a result, the monkey was unable to lift and maintain the object within the position window for the required 2 s, and, over time, the grip force decreased progressively until the animal stopped working. Following SI injections, the most obvious effect was a loss of finger coordination. In grasping, the placement of the fingers on the object was often abnormal and the monkey seemed unable to control the application of prehensile and lifting forces. However, the detailed analysis of forces revealed that a substantial increase in the grip force occurred well before any deficit in the coordination of finger movements was noted. This observation suggests that cutaneous feedback to SI is essential for the fine control of grip forces.

Key words Hand movements · Monkey · GABAergic inhibition · Cortex · Motor control · Grip force

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Introduction

In the execution of prehensile movements, the fingers are generally accurately abducted and extended to match the size of the object (Jeannerod 1984, 1986). Studies of the motor behavior of patients with complete somatosensory loss have demonstrated the critical role played by proprioceptive and cutaneous feedback in controlling prehensile movements (Fleury et al. 1995; Rothwell et al. 1982; Sanes et al. 1985; Teasdale et al. 1993). Patients with severe or total sensory loss have significant deficits in fine manipulation, such as fastening a button or picking up small objects. Similar deficits have also been reported in a patient with a lesion of SI (Jeannerod et al. 1984), suggesting that this cortical area may contribute to the control of precision handling by conveying cutaneous feedback to the more anterior motor areas. In agreement with this hypothesis, Hikosaka et al. (1985) reported that, following reversible inactivation of SI by muscimol injections, monkeys display significant deficits in manual dexterity.

Dexterous hand movements and precision grasping also involve the fine control of the forces required to grip and lift target objects (Westling and Johansson 1984). Cutaneous feedback is essential for these force adjustments since local anesthesia of the tip of the thumb and index finger causes severe deficits in the ability of human subjects to adapt their grip force to the surface friction of a grasped object (Johansson and Westling 1984). Several lines of evidence suggest that the coordination of grasping and lifting forces are mediated by afferent information processed within SI and

MI. The triggered prehensile responses induced either by slips on the skin or electrical stimulation of digital nerves occur within 50–100 ms, which is compatible with supra-spinal processing of sensory information (Johansson and Westling 1984). Also, single-unit recording studies in behaving monkeys have revealed that the neural activity within SI and MI is closely related to changes in the surface friction of objects during precision lifting and holding (Picard and Smith 1992a, 1992b; Salimi et al. 1999a, 1999b, 1999c). The same cells which respond to object texture and surface friction also respond to force-pulse perturbations at a latency of about 40 ms. In addition, S1 and MI neurons with similar cutaneous receptive fields present some other striking similarities in their discharge patterns during grasping and lifting movements as well. Together, these observations suggest a close relationship between the two cortical areas in controlling the precision grip. However, to date, there has been little direct evidence that these cortical areas are essential to the fine control of the grip and load forces.

The present study was designed to evaluate to what extent SI and MI are involved in the precise regulatory control of hand musculature. The ability of a monkey to perform a precision grip task using haptic cues was analyzed following reversible inactivation of either SI or MI by local injection of the $GABA_A$-agonist muscimol. The task used a computer-controlled, instrumented object to assess the forces applied by a monkey during grasping and lifting. In addition, a qualitative analysis of the deficits in controlling independent finger movements under visual guidance was performed to facilitate a comparison with the study by Hikosaka et al. (1985).

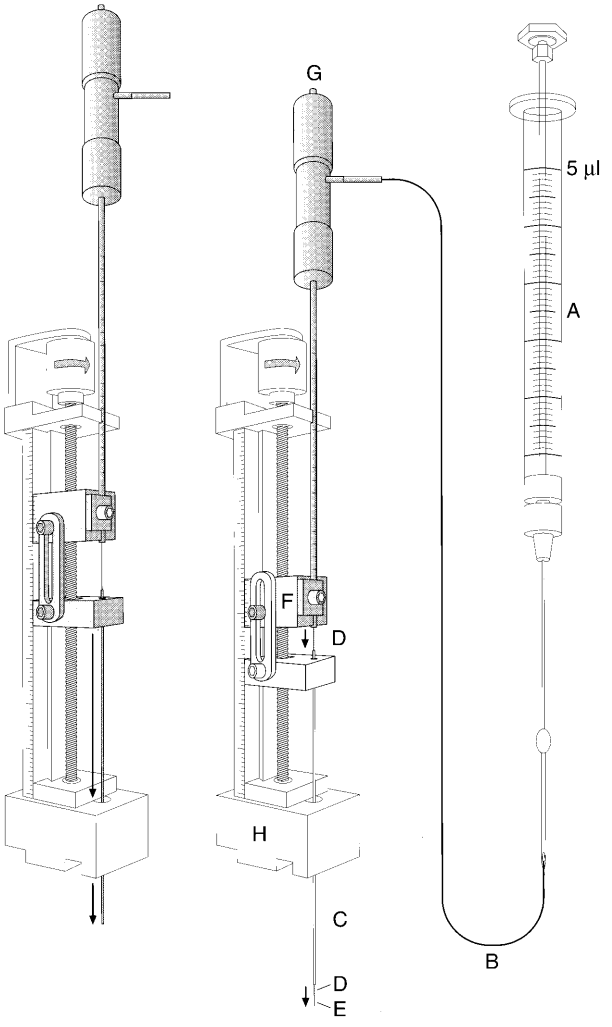

Fig. 1 The canula system used for muscimol injection. At *left*, the injection system is shown with the microwire and the inner canula within the external canula prior to penetration (*arrow*) of the dura matter. In the *middle*, the injection system is illustrated after dura penetration. The external canula is fixed and both the inner canula and the microwire are advanced within the cortex (*arrow*). The moving parts are shaded *gray*. *A* Hamilton syringe (5 µl), *B* polyethylene tube, *C* external canula, *D* inner canula, *E* stainless steel microwire, *F* screw drive manipulator, *G* microwire connector, *H* system armature allowing fixation of the canula onto the X-Y micropositioner

Materials and methods

A single female monkey (*macaca fascicularis*), weighing 2.8 kg, was used in the present study. Prior to the muscimol injections, this monkey was the subject of extensive cortical single-unit recording, which provided a detailed map of the area of the thumb and index-finger representation. However, only data related to the effects of muscimol injections are reported here.

Motor tasks

The monkey was seated in a primate chair with the head immobilized for single-cell recording and the arm and forearm restrained by a support at the elbow and wrist allowing the hand to move freely at the wrist. The hand and manipulandum were positioned beyond the monkey's visual field and a head-restraint device prevented the monkey from looking at its hand. The animal was trained to use a precision grip to grasp a metal tab attached to the armature of a linear motor between the thumb and index finger. The task requirement was to correctly lift the object into a vertical position window of 12–25 mm, signaled by a 1 kHz tone, and to hold it stationary for 2 s to obtain a fruit juice reward. Once the monkey had released the object at the end of each trial, an intertrial interval of 1.5 s was imposed before a subsequent trial could be initiated. The metal tab in contact with the fingers was covered with very coarse sandpaper (grit size 40), which provided a high friction surface on the skin. The linear motor generated a downward force of 0.6 N to simulate an object weighting approximately 60 g. The computer-controlled object measured both the grip and lifting forces and vertical position. Trials were recorded if the monkey succeeded in raising the object within the position window, even if it failed to maintain the position for the requisite duration (i.e., error trials).

In order to assess the monkey's performance in more natural grasping behaviors as described in previous studies (Hikosaka et al. 1985; Matsumura et al. 1991; Schieber and Poliakov 1998), we also included a second task which consisted of a modified Klüver board (Lawrence and Kuypers 1968). In this task, the animal had to use a precision grip to extract small pieces (3–8 mm cubes) of food from a series of narrow, recessed wells (24 mm diameter, 12 mm deep). Since the monkey's entire hand could not penetrate the food wells, the animal was obliged to use only two fingers for grasping. The monkey was permitted to use only one hand to retrieve the food. This task tested the monkey's performance under both visual and non-visual control conditions.

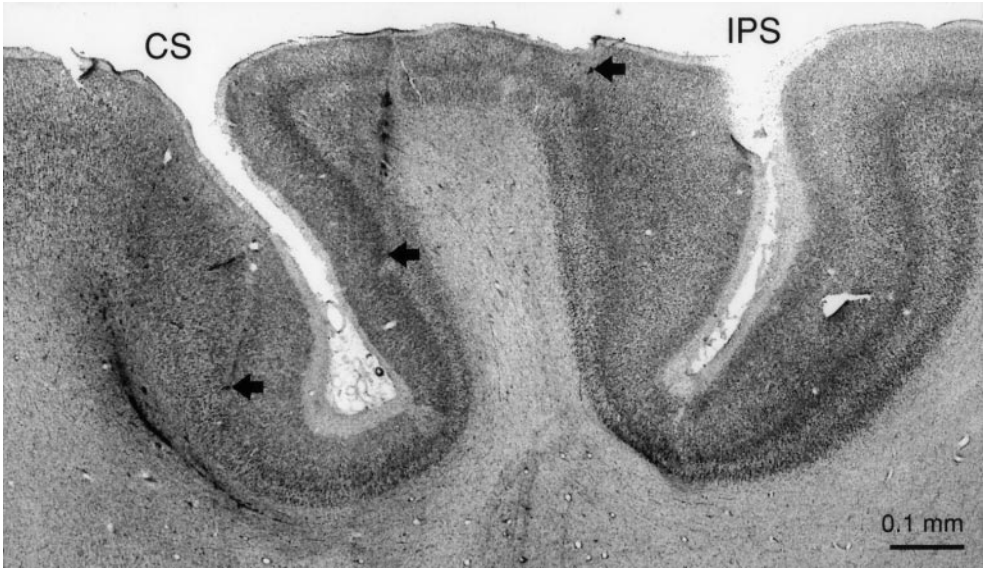

Fig. 2 Parasagittal section through the index representation of the primary somatosensory (SI) and motor (MI) cortex. The section is stained with cresyl violet. *Black arrows* indicate three obvious sites of injection within area 4 (*left arrow*), area 3b (*central arrow*), and area 2 (*right arrow*). *CS* Central sulcus, *IPS* intraparietal sulcus

Surgery and experimental procedures

After completion of the training period, a craniotomy was performed and a 18 mm circular recording stainless-steel chamber was implanted stereotaxically over the thumb and index region of SI and MI contralateral to the trained hand. As mentioned above, prior to the inactivation experiments, extensive recording of single-cell receptive fields and responses to intracortical microstimulation (0.2 ms pulses, 300 Hz, 100 ms train duration, maximum 30 µA) were used to map the area of thumb and index finger representation in SI and MI. The coordinates of these areas were used as targets for the muscimol injections.

Inactivation experiments

Muscimol was injected with a 5 µl Hamilton syringe connected by a polyethylene tubing to a canula system mounted on the X-Y micropositioner previously used for single-unit recordings (Trent Wells, 3-0435). The injection system included a robust external steel canula (diameter 25 gauge) with a beveled tip used to penetrate the dura mater (Fig. 1). A smaller inner canula (31 gauge) inserted in the external canula carried an insulated stainless steel microwire (50 µm), which was used for cell recording and microstimulation. Once the external canula had penetrated the cortex, it was immobilized and a screwdrive manipulator advanced the internal canula and the stainless steel filament independently from the external canula. Cortical inactivations were achieved with two 1.0 µl injections of the $GABA_A$ agonist, muscimol (5 µg/µl), into the thumb and index regions of either the pre- or postcentral gyrus. The injection sites were located 1.0 mm apart in the mediolateral plane. The hand movements, both in the experimental grasping task and in the food grasping task, were recorded with a video-camera (60 frames/s). For both tasks, control data were obtained from ≈35 trials performed both prior to each injection and on the day following the injection.

Histological processing

At the end of the experiment, the animal was killed with an overdose of pentobarbital and perfused transcardially with 0.9% saline followed by 4% paraformaldehyde. The brain was immersed in a solution of sucrose (20%, 4°C) for 24 h for cryoprotection before freezing (–80°C). Frozen sections (40 µm thick) were cut in a plane perpendicular to the central and intraparietal sulci. The sections were stained with cresyl violet and were used for reconstructing the investigated regions.

Results

Overall, seven injections were attempted. Of these, five were successful (two in MI, three in SI). Of the other two injections that did not show any significant behavioral effects, one was located too deeply in the white mater, whereas the other one was a single injection in SI.

Histology

The cresyl violet section depicted in Fig. 2 shows three sites of injection within the finger representation of the sensorimotor cortex. In MI, the injections were concentrated deep in the anterior wall of the central sulcus. Injections in SI were located in the posterior wall of the central sulcus in area 3b and also more caudally in area 2. Receptive-field examination revealed that the more medial tracks were within the digit 2–5 representation, whereas the lateral tracks were localized in the thumb area.

Behavioral data

The monkey was trained for several months on the grasp, lift, and hold task before the inactivation studies began, and therefore the grasping and lifting movements were highly over-trained and stereotyped. Between trials, the hand remained motionless above the display without touching the lifting tab for the duration of the 1.5 s intertrial interval (Fig. 3A1). Grasping began as the monkey moved the hand toward the metal tab and simultaneously opened the thumb and index finger (Fig. 3A2). As soon as the fingers contacted the grasping surface, they were accurately positioned in opposition on both sides of the metal tab, allowing rapid and precise lifting movements into the position window (Fig. 3A3–5). This grasping and lifting sequence was affected differently by muscimol injection into either SI or MI.

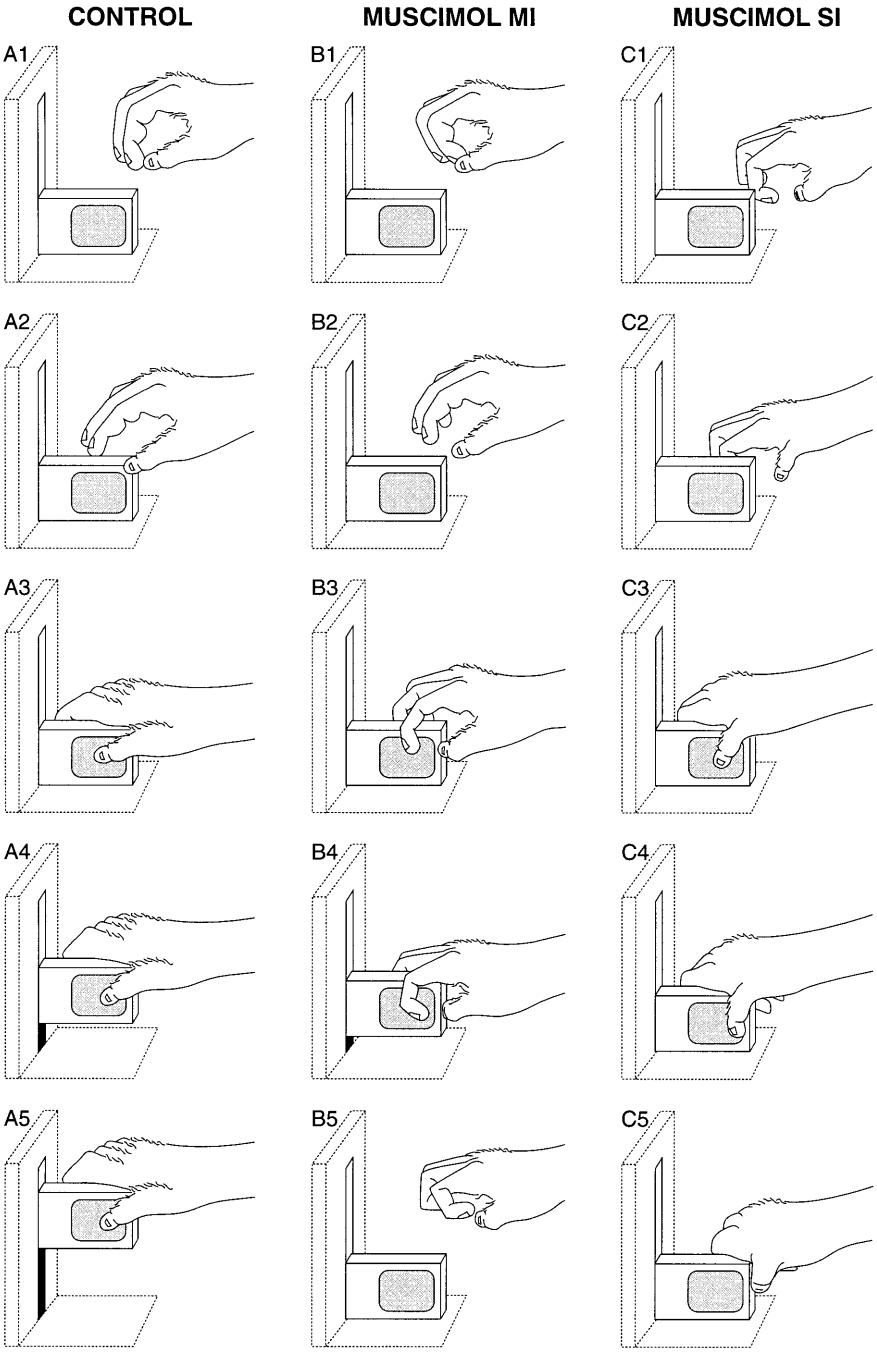

Fig. 3A–C Grasping and lifting sequence performed by the monkey in the experimental situation before (column **A**) or after muscimol injection within SI or MI (columns **C** and **B**, respectively). Temporal sequence from top to bottom. See text for details

MI injections

MI injections initially produced an inability to maintain the object within the position window for 2 s to obtain a reward. During this early period, there was no obvious disturbances in the finger movements used to grasp and lift the object. Between 15 and 30 min after the double injection, all attempts to maintain grasping for 2 s failed and the monkey rapidly stopped working even if rewards were given for any attempts to perform the task. At this stage, the hand and fingers were not paralyzed, but a significant weakness in grip strength was noted. For example, the monkey couldn't apply enough force to grasp a food morsel gently held between the thumb and index finger by the experimenter. The motor deficit was restricted to the most distal segments of the hand. Even in the final trials recorded in the experimental task, the monkey could still accurately move the hand from the intertrial position above the display (Fig. 3B1) to the object surface (Fig. 3B2). However it seemed that the fingers couldn't extend sufficiently for an accurate adjustment of the grasp aperture, and there was no evidence of independent finger movements. Instead, all the fingers moved together in whole-hand grasping. This loss of the precision grip often resulted in aberrant positions of the fingers on the grip surfaces, and the object was frequent-

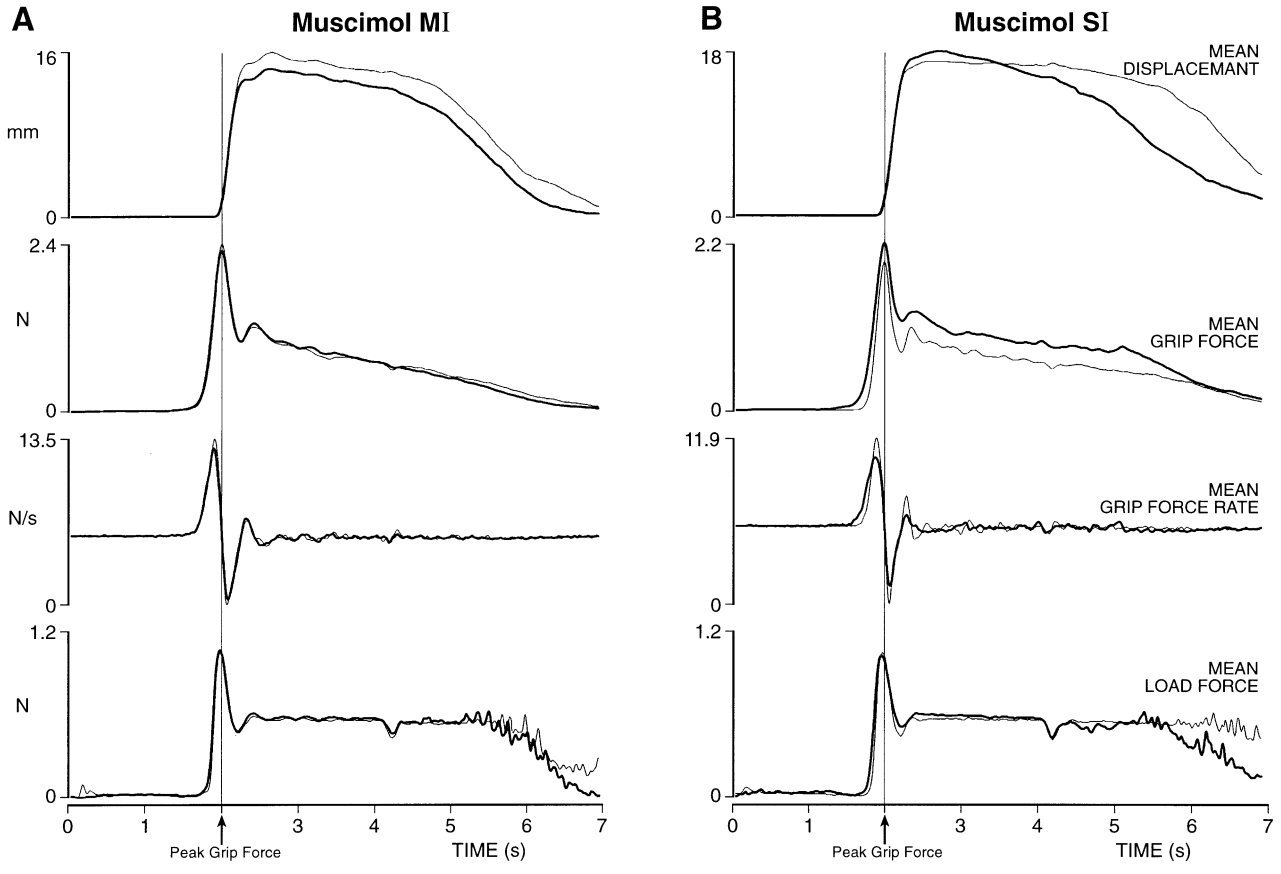

Fig. 4A, B From *top* to *bottom*, mean object displacement, mean grip force, mean grip force rate, and mean load force averaged over 30 control trials before injection (*thin lines*) and the 30 last successful trials after injection (*thick line*). **A** Muscimol injection in primary motor cortex (*MI*), **B** injection in primary somatosensory cortex (*SI*, area 2). All the trials have been synchronized on the peak grip force (*arrow*). The dip in the load force at 4 s is an artifact due to the reward at the end of the holding period

ly released before lifting was completed (Fig. 3B3–5). In other failed trials, the monkey seemed unable to apply sufficient grip and load forces to lift and hold the object within the position window. Finally, in the food-grasping task, the monkey was unable to oppose the thumb and index finger to enter the food well, even when the movement was executed under visual control.

SI injections

Profound deficits in the precision grip were also noted following SI injections, but they were readily distinguishable from the MI-induced deficits. The first visible effect of SI inactivation was the monkey's inability to coordinate the finger movements in order to position the thumb and index finger for accurate grasping. This effect appeared between 15 and 45 min following the second injection, and it was not observed when only a single injection was given. This deficit was certainly not related to motor weakness, since the monkey could still actively move its hand and fingers over the object. Many rapid wiping and stroking movements were performed over and about the metal tab, but these exploratory movements rarely led to actual grasping. Also, the muscle strength appeared to be unaffected. If sufficiently rewarded and motivated in the task, the monkey could be kept working even when all the trials failed because of inaccurate finger placement. On some occasions, the object was tossed up and down with force and apparent irritation. Also, the monkey clearly had enough force to push the experimenter's hand away when it prevented the monkey from grasping the object.

One strategy used by the monkey to compensate for these deficits was to keep the hand as near as possible to the grasping surface during the intertrial interval (Fig. 3C1), which facilitated bringing the hand toward the metal tab for grasping (Fig. 3C2). At first, this strategy led to accurate positioning of the fingers on the grasping surfaces, but the lifting movement rapidly deteriorated (Fig. 3C3–5). It seemed that the grip and lifting forces were misapplied and misdirected in grasping and lifting the object. Therefore, despite the fact that the object was covered with sandpaper, providing a high friction surface, the fingers still slipped over the surface and, as a result, the object was either lost before lifting or rapidly dropped during the holding phase.

Deficits in the precision grip were similarly observed in food grasping behavior. When visual feedback was prevented, the monkey failed to introduce the thumb and

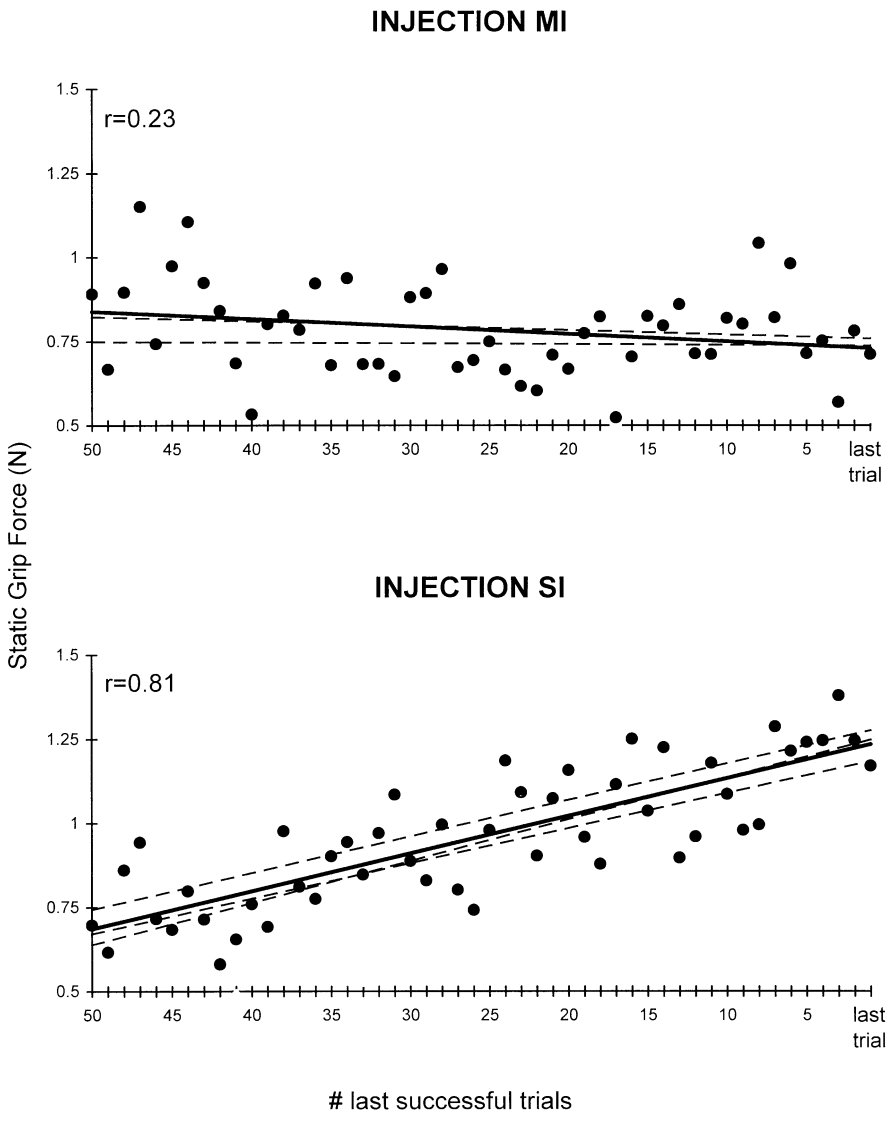

Fig. 5 Variations in the static grip force following muscimol injection within the primary motor cortex (*MI*) and primary somatosensory cortex (*SI*). The data are presented in a chronological order from the 50th trial (*left*) to the last successful trial (*right*) recorded before the monkey performed only error trials. Each *black dot* represents the mean static grip force averaged over the two injections (*upper graphic*) or the three SI injections (*lower graphic*). The *thick lines* indicate the regression line for these average values of static grip force. The *dotted lines* indicate the regression lines calculated for each separate injection (the individual values of static grip force measured for each separate injection are not shown in the graphic). Note that a progressive increase in static grip force was consistently observed over the three SI injections, but not after the MI injections

index finger simultaneously into the food well except by chance and, in which case, the monkey seemed unable to feel and locate the food. This grasping behavior was somewhat improved under visual control. Although awkward, the monkey could use the thumb and index finger to perform a precision grip and was able to bring food to the mouth. To compensate for movement inaccuracies, the digits 3, 4, and 5 were often recruited to stabilized the food morsels in the hand.

Force control during precision grasping and lifting

Both before inactivation and after recovery, the monkey grasped and lifted the object using a stereotyped pattern of grip and load force. This pattern remained almost unchanged from trial to trial and was similar to the pattern described in previous papers (Dugas and Smith 1992; Salimi et al. 1999a). Briefly, when the fingers contacted the object surface, the grip force started to increase rapidly and a parallel increase in load force was initiated between 70 and 120 ms after grip onset (Fig. 4, control traces). Once the load force was sufficient to overcome object mass, the object moved toward the position window. During this dynamic lifting phase, the load force varied in proportion to the object acceleration and deceleration, but it remained at an unchanging level during the static holding phase. Following a transient peak, the grip force was adjusted to the friction and simulated weight of the object and it remained nearly constant throughout stationary holding. Depending on the recording session, the object position was either held stationary (Fig. 4B) or was gradually lowered throughout the holding phase (Fig. 4A).

MI injections

During the first 5–10 min following the double injections, the pattern of the grip and load forces used to lift

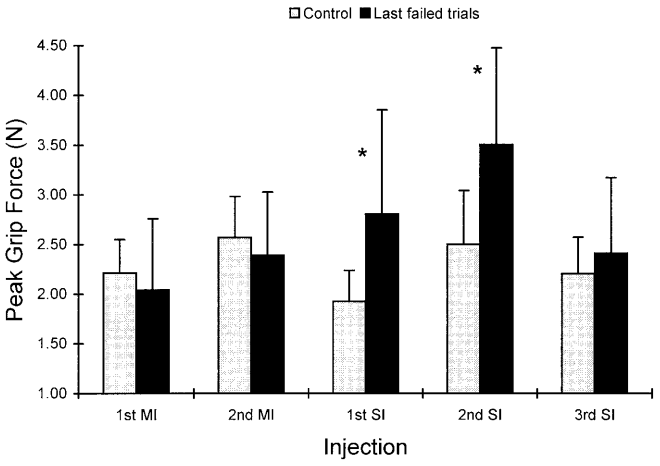

Fig. 6 Mean peak grip force measured over 15 control trials and the 15 last error trials for each separate muscimol injection. * indicates a significant difference between control and post-injection values (Student's *t*-test, $P<0.05$). Although the initial level of grip force changed from day to day, the effects of muscimol injection were consistent over primary somatosensory and motor cortex inactivations

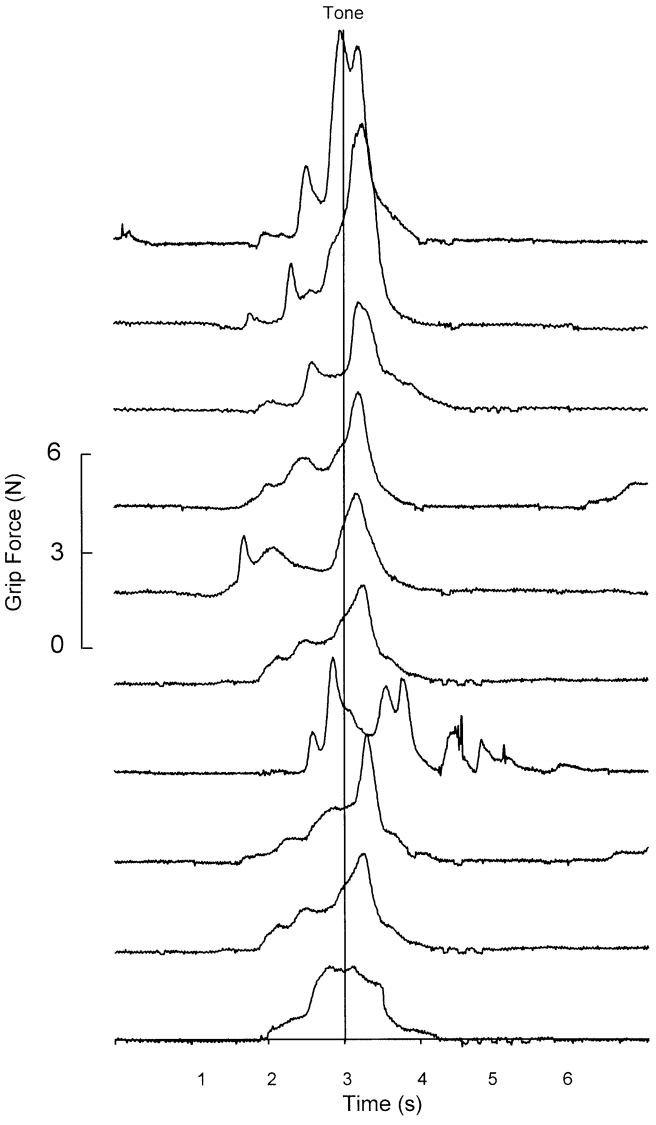

Fig. 7 Pattern of grip force variation observed after muscimol injection in primary somatosensory cortex (SI). All the trials are error trials recorded just before the monkey stopped working. The synchronization is on the tone, i.e., when the object entered the vertical position window. A comparison with Fig. 4 shows that the increase in grip force was longer and more irregular than in the control trials and that a constant level of grip force could not be maintained during the holding period

the object remained almost unaffected (Fig. 4A). There did not appear to be any significant changes in the absolute level of grip force used to hold the object stationary (Fig. 5) among the last successful trials. In fact, the only perceptible effect was a slight decrease in the height of the held position (Fig. 4A). After 10–15 min, however, performance deteriorated rapidly, and it appeared that the monkey was unable to maintain a grip for 2 s, even when the thumb and index finger were correctly placed on the metal tab. This inability to perform the task was undoubtedly due to a progressive weakness in the hand and finger muscles. Indeed, the average peak grip force calculated over the 15 last failed trials was lower than the peak grip force measured on the successful trials before injection (Fig. 6). Although this effect was not statistically significant, it reflected a reliable tendency observed on two separate MI inactivations. Moreover, it is likely that, if the monkey had attempted lifting using an insufficient grip force, it would have been unable to lift and maintain the object within the vertical position window. Such a reduction in grip force seemed to occur after 30 min, toward the end of the recording session, just before the monkey eventually stopped working.

SI injections

In contrast to MI injection, after SI injection the monkey kept working with no apparent difficulty for about 15 min. The finger movements were accurately coordinated and the object was maintained within the position window for the 2 s holding period. However, the quantitative data analysis revealed persistent increases in the forces used during the task. The grip force was increased both during the dynamic lifting phase and during the static holding period compared with the control trials recorded just before injection (see Fig. 4B). As illustrated in Fig. 5, the increase in peak grip force was very gradual over the last 50 successful trials and the force went from an average value of 0.75 N to more than 1.1 N. This effect was observed consistently in three separate muscimol inactivations of SI. Despite these adjustments in grip force, the grasping and lifting sequence became less coordinated and errors became increasingly frequent. On the last error trials before the end of the recording session, the peak grip force was higher than in the control situation (Fig. 6). However, the grip force was not maintained during the static phase, presumably

because of the absence of sensory feedback, and the object was systematically released before the required 2 s had elapsed.

Another consequence of SI inactivation was the increased variability in the rate of application of grip force during the dynamic lifting phase. In general, this effect was particularly obvious at the end of the session when the sensory deficit induced by the muscimol injection was maximal. When the fingers contacted the object surface, the grip force was increased irregularly and in a multiple step-like fashion. Instead of the single sharp peak observed in the control trials, one or two intermediate peaks were recorded before the object entered the position window (Fig. 7). Also, the monkey increased the number of palpating movements and small probing pressures on the object, probably to compensate for the loss of cutaneous feedback during the intertrial interval. On some occasions, the fingers were accurately positioned and this strategy led to an actual lifting movement.

Discussion

This study shows that the reversible inactivation of the finger representation of SI or MI of the monkey produced two types of deficits. The first involved the control of prehensile movements, or the ability to accurately position the thumb and index finger prior to grasping and lifting the object. This type of deficit was obvious in a variety of grasping behaviors and was summarized in a qualitative description. The second type of deficit was related to the adjustment of the grasping and lifting forces once the fingers had contacted the object surface. This type of deficit was not systematically associated with movement clumsiness, and it would have gone unnoticed if no suitable device had been available to measure the changes in the horizontal grip force and the vertical load force during grasping and lifting. No such deficits were observed following a single injection in SI, suggesting that the monkey could compensate for a partial inactivation affecting only one finger. No single injection was attempted in MI. The effects observed following double injections in either area SI or MI were readily distinguishable from each other.

The effects of MI inactivation

Overall, the main effect of inactivating the thumb and index representation area of MI in our monkey was the inability to perform independent finger movements in association with a general muscular weakness in the hand. This effect was illustrated by the monkey's inability to accurately position the thumb and index fingers on both sides of the object (Fig. 3B3–B5), even though the haptic feedback was thought to be spared by the MI cortical inactivation. These results were very similar to deficits caused by bilateral pyramidal lesions (Lawrence and Kuypers 1968) or by MI excision (Passingham et al. 1983). Lawrence and Kuypers (1968) observed the motor behavior of 41 monkeys following lesion of the pyramidal tract and stated that "individual finger movements never returned, even after recovery periods of up to eleven months. In addition, all the movements were slower and fatigued more rapidly than in the normal animals". The whole-hand grasping used by our monkey to perform the experimental task after MI injection resembled these observations and agrees with similar descriptions of the loss of independent finger movements after reversible muscimol inactivations of the motor cortical hand area (Schieber and Poliakov 1998). Together, these studies add further support to the suggestion that the corticomotoneuronal fibers play a special role in the performance of individual finger movements. There is a general agreement that the direct corticomotoneuronal projection originating from MI terminates on the motoneurons of intrinsic hand muscles contralaterally and play an important role in precision handling (Lawrence and Hopkins 1976; Muir and Lemon 1983). Furthermore, Lemon and colleagues (1986, 1990) have suggested that the corticomotoneuronal cells related to finger movements are mostly located in the posterior part of MI, i.e., within the anterior wall of the precentral gyrus in a region known to receive a strong cutaneous input (Strick and Preston 1982; Picard and Smith 1992a). In the present study, the muscimol injections were restricted to this cortical area and, as yet, no injections has been performed in the more anterior superficial convexity of the precentral gyrus. It is doubtful, however, that more rostral injections would have produced more pronounced deficits.

Also, in agreement with the study of Kubota (1996) on the effect of MI inactivation with muscimol, we observed that the injection-induced deficits were more pronounced on finger extension than flexion. Although the monkey could separate the thumb and index finger to a certain extent after injection (Fig. 4B2), this may have reflected a relaxation of the flexor muscles rather than an true extension and finger abduction. Whereas several muscles control finger flexion, a single muscle is involved with finger extension (i.e., the extensor digitorum communis). In a study of the monosynaptic excitatory effects of MI neurons on spinal motoneurons, Clough et al. (1968) observed that the cortical monosynaptic excitatory post-synaptic potentials (CM EPSPs) were larger on the motoneurons innervating intrinsic hand muscles and on the motoneurons of the extensor digitorum communis. Therefore, it is likely that inactivation of the corticomotoneuronal pathways would primarily affect the ability of the monkey to perform independent finger movements and whole-hand finger extension.

It is worth noting that the muscimol induced deficits observed in our study were very similar to those reported by Schieber and Poliakov (1998), but differed to a certain extent from the effects described by Matsumura et al. (1991) and Kubota (1996). In the present study as well as in the study of Schieber and Poliakov (1998), sustained deficits of precision grip were still observed as late as 1 or 2 h after cortical inactivation. In contrast,

Mastamura et al. (1991), who described a marked deficit of precision grasping between 10 and 30 min after injection, stated that this deficit reversed rapidly and decayed within 60 min post-injection. This difference might be explained by the fact that Matsumura et al. (1991) injected low doses of muscimol (2 µg) to inactivate cortical activity, in comparison with the 5–10 µg doses injected by Schieber and Poliakov (1998) and the two doses of 5 µg used in the present study. A complementary explanation could be that, in our study, the injections sites were precisely located in the thumb and index finger representation of the deep motor cortex, whereas Matsumura et al. (1991) injected in a more generally defined hand area in the precentral sulcus. On the other hand, the muscimol induced deficits appeared less profound in our study than in Kubota's (1996) report. As shown in Fig. 4B1–B5, our monkey could still perform whole-hand and crude prehensile movements, which did not appear to be the case in Kubota's (1996) observation. Again, this discrepancy might be related to the fact that we injected two doses of 5 µg of muscimol in the awake monkey, whereas Kubota injected more concentrated doses of muscimol (30 µg/µl) in anesthetized monkeys and reported the behavioral effects in the animal recovering from anesthesia. Overall, these comparisons strongly suggest a tight relationship between the volume of muscimol used to inactivate cortical activity and the strength and duration of the corresponding behavioral deficits.

Finally, in agreement with previous studies (Mastumura et al. 1991; Schieber and Poliakov 1998), our observations confirm that muscular weakness is one of the main consequence of MI inactivation. In addition, our study provides quantitative evidence of the effect of muscular weakness on grip force. Following injection, the monkey continued working as long as he could produce enough force to grasp and lift the object. At the end of the recording session, the grip force diminished rapidly and, combined with the loss of independent finger movements, caused a significant deficit in task performance.

The effects of SI inactivation

The most obvious effect of inactivating the hand representation in SI was a loss of manual coordination during object grasping. In line with the observations of Hikosaka et al. (1985), our monkey was unable to accurately oppose the tips of the thumb and index finger in an attempt to grasp small food morsels in recessed wells. In addition, cutaneous sensation from the fingers seemed strongly impaired since the monkey appeared unable to feel the contact between the skin and the food, even when contact occurred by chance. The performance was somewhat improved under visual control, demonstrating the ability of the monkey to execute some crude independent finger movements when other sources of feedback were available. These deficits in the control of prehensile movements induced by muscimol injection are similar to deficits observed in man or monkey following lesions of the somatosensory pathways either at the cortical level (Jeannerod et al. 1984; Kruger and Porter 1958; Peele 1944), or at the level of the dorsal column nuclei (Eidelberg et al. 1976; Gilman and Denny-Brown 1966; Glendinning et al. 1992; Leonard et al. 1992) or following peripheral deafferentation (Fleury et al. 1995; Rothwell et al. 1982; Sanes et al. 1985; Teasdale et al. 1995). Together, these studies emphasize the importance of somatosensory afferents to SI for the execution of coordinated finger movements.

The progressive increases in the grip forces after muscimol inactivation of SI represents the original contribution contained in the present study. It has been proposed that the detection of slips on the skin is a critical factor in maintaining a secure precision grip (Westling and Johansson 1987). Therefore, it is likely that increasing the grip force was a strategy used by the monkey to restore a more secure grasp as soon as the sensitivity to slips was diminished by muscimol inactivation. Interestingly, the increase in grip force was observed during successful trials even before any clumsiness in the prehensile movements could be detected. This observation further supports the idea that the sensorimotor control of grip force is closely dependent on cutaneous feedback to SI, and that compensatory strategies are required for even a moderate level of SI inactivation. Furthermore, in agreement with the hypothesis that the detection of slips is cortically mediated, we have recorded a group of cells with a special sensitivity to slips on the skin within SI of awake monkeys (Salimi et al. 1999c). The inactivation of these cortical cells would reduce the ability of the monkey to produce rapid responses to slips.

Johansson and Westling (1984) found that human subjects in whom the skin of the finger tips had been subjected to local anesthesia increased the force building time. The muscimol inactivation of SI appeared to have a similar effect. This effect was only observed when the cortical inactivation was more pronounced shortly before the monkey refused to make further lift and hold movements. We suggest that the long and irregular increases in grip force before lifting was due to a probing strategy used by the monkey in an attempt to improve cutaneous feedback. Also, in order to compensate for the loss of cutaneous feedback, the monkey increased the number of palpating movements and small exploratory pressures on the object during the intertrial interval. In general, such exploratory strategies are associated with the need for additional feedback either because some physical features of the object, such as weight or surface friction, has been unexpectedly altered (Westling et Johansson 1984) or because the cutaneous acuity is diminished.

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