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ORIGINAL COMMUNICATION

Dennis A. Nowak
Joachim Hermsdörfer
Helge Topka

Deficits of predictive grip force control during object manipulation in acute stroke

Abstract Anticipatory grip force adjustments when lifting, holding and performing vertical point-to-point movements with a hand-held object were analysed in 11 patients with deficits of fine manual motor performance due to acute ischemic stroke. All patients had mild to moderate paresis and sensory deficits of the affected hand. Grip forces used to stabilise the object in the hand, accelerations of the object and movement-induced loads were measured. Compared with controls, patients produced markedly increased grip forces when lifting, holding and moving the hand-held object. The ratio between grip force and the actual load, which is considered to be a sensitive measure of force efficiency, was significantly elevated in stroke patients indicating a strategic generalisation of grip force increase when cerebral sensorimotor areas are functionally impaired. The temporal coupling between grip and load force profiles revealed only selective impairments during the lifting and movement tasks of stroke patients. The time to reach maximum grip force was prolonged and there were greater time lags between grip and load force maxima during the lifting movements. When healthy controls performed vertical movements with the hand-held object grip force increased early in upward and late in downward movements and grip and load force maxima coincided closely in time. The time lags between maximum grip and load forces were similar for vertical movements performed by patients and controls. However, the time lags between grip force and acceleration onset were larger for upward and smaller for downward movements performed by stroke patients. These findings indicate impaired prediction of the inertial load profiles arising from voluntary arm movements with a hand-held object in acute stroke.

Key words grip force · object manipulation · sensorimotor performance · feed-forward control · acute ischemic stroke

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J. Hermsdörfer
Entwicklungsgruppe Klinische Neuropsychologie
Abteilung für Neuropsychologie
Krankenhaus München-Bogenhausen
Dachauerstr. 164
80992 München, Germany

Dr. D. A. Nowak (✉) · H. Topka
Abteilung für Neurologie und Klinische Neurophysiologie
Krankenhaus München-Bogenhausen
Akademisches Lehrkrankenhaus der Technischen Universität
Englschalkingerstraße 77
81925 München, Germany
Tel.: +49-89/9270-2259
Fax: +49-89/9270-2684
E-Mail: Dr.Dennis.Nowak@gmx.de

Introduction

Despite success in reducing the mortality and morbidity from ischemic stroke, many stroke survivors continue to have serious functional impairments, particularly in motor function of the affected hand. In clinical examinations manual performance is usually tested using crude tasks, such as maximum force production and coordination of the hand and arm when grasping for objects [3, 6, 14, 24, 35]. Such gross measures of performance fail to establish which components of fine finger motor behavior are disrupted and which components are preserved providing a possible target for individual rehabilitation [25, 29].

The precise control of grip force according to the physical requirements of a manipulated object is a fundamental aspect of skilled motor performance of the hand. Healthy subjects regulate finger forces in anticipation of physical object properties, such as weight, surface

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friction and shape [20, 23]. In addition, grip forces not only anticipate static object properties, but also dynamic loads that arise when a hand-held object is moved around in space [11, 43]. In this situation, the grip force profile is modulated in parallel with acceleration-induced fluctuations in load force indicating predictive feed-forward control of prehensile finger forces. An internal forward model, responsible for the integration of the limb dynamics and its implications on the loading of a hand-held object, has been suggested [2, 12, 44].

Apart from studies analysing maximum grip strength [3, 24], some elementary aspects of prehensile finger force control have been studied in chronic stroke patients, such as force tracking [19, 29], production of diadochokinetic force changes [18, 29] and reaction to sudden load perturbation of a hand-held object [15]. However, systematic studies investigating grip force control during natural voluntary object manipulations in patients with acute stroke are not available. Such studies may provide an objective measure of impaired hand function in stroke patients. In addition, analysis of manual performance in ischemic cerebral lesions contributes to the understanding of the complex process of predictive grip force regulation and its dysfunction. Here we study grip force control during stationary and dynamic manipulative tasks among patients with mild to moderate sensorimotor deficits of the affected hand due to an acute single cerebrovascular accident. Subjects lifted and held an object (equipped with measuring instruments) and then performed vertical point-to-point movements with the hand-held object with the affected hand. We compared the performance of the affected hand of stroke patients with the hand dominance-matched hand of healthy controls.

Sensory deficits are a frequent consequence of stroke that may result in profound disability in the activities of daily living [19, 37]. It has been repeatedly demonstrated that deterioration of peripheral sensory input due to digital anesthesia [23, 32] or pathological conditions [41, 42] impair the economical scaling of the grip force magnitude in relation to the actual load of a manipulated object. From these observations we suggest that there are elevated grip forces of the affected hand in stroke patients with additional sensorimotor disturbances. However, selective impairment of descending motor pathways may also cause an increase of the grip force level during voluntary object manipulation [34].

The close temporal coupling between grip and load force profiles when manipulating objects is particularly striking in healthy subjects. For example, maximum grip force coincides with maximum upward acceleration when an object is grasped and lifted [23]. During vertical point-to-point movements with a grasped object grip force normally rises early in upward and late in downward movements and grip and load force maxima coincide closely in time [11, 43]. Only slight disturbances of the grip force – load force coupling have been reported in hemiparetic patients performing a drawer opening task [15] and in children with congenital cerebral palsy grasping and lifting an object [8, 13]. We therefore expect the temporal regulation of the grip force profile to be principally preserved in acute stroke patients manipulating an object.

Material and methods

Patients

11 patients suffering from a first ischemic stroke participated in the study within two weeks from the onset of symptoms (5 female, 6 male, mean age 65.3 years). All patients experienced an unilateral cerebral ischemic stroke. In 5 patients the ischemia affected the left hemisphere, in 5 patients the ischemic lesion was located in the right hemisphere and in one patient the ischemia affected the brainstem. All patients but one were right-handed and in five patients the ischemic lesion affected the dominant hand. In all cases but one the cerebral ischemia occurred within the territory of the middle cerebral artery, eventually with additional minor ischemic lesions in the neighbouring cerebrovascular territories. All patients were hospitalised in the Department of Neurology and Clinical Neurophysiology of the Academic Hospital Bogenhausen at the time the experiments were conducted. The clinical and demographic data of the patients are summarised in Table 1. The National Institute of Health Stroke Scale [4] was assessed at the time of the experimental session and was between 3–11 points (mean 7.5 points). The time between the onset of stroke to the experimental session varied between 2–12 days (mean 7 days).

Patients were selected when clinical examination revealed deficits of fine motor control of the hand. In Table 1 the scores assessed by clinical examination are summarised for each patient. All patients had mild to moderate paresis of the affected hand and all had additional sensory deficits of the grasping fingers. All patients were able to grasp and manipulate the object used. None of the patients exhibited pronounced spasticity of the affected upper extremity that may have hampered task performance.

Eleven healthy age- and sex-matched subjects without any history of neurological disorders served as controls (mean age 65.1 years). All control subjects were right handed. All participants were completely naive with regard to the specific purpose of the experiments. Informed consent was obtained from all participants; the study was conducted in accordance with the Declaration of Helsinki and was approved by the local Ethics committee.

Instrumented object

Patients and control subjects grasped a cylindrical and cordless instrumented object between the tips of the thumb and other fingers on either side. The manipulandum [32–34] and the configuration of the hand and fingers used to grasp it are illustrated in Fig. 1. The mass of the object was 0.350 kg. The object had a diameter of 9.0 cm and a depth of 4.0 cm. Grip surfaces were of polished aluminum in all trials performed. The object incorporated a force sensor for grip force recording and linear acceleration sensors for recording of kinematic acceleration signals in three dimensions (see Fig. 1). The force sensor registered grip forces up to 50 N (digital resolution: 0.0125 N/Bit). The linear acceleration sensors measured linear acceleration within a range of ± 50 m/s^2. The center of mass of the manipulandum was halfway between the points at which the fingers contacted its surfaces. Recorded grip force and acceleration data were A-to-D-converted with a sampling rate of 100 Hz and stored within the manipulandum by a FLASH data storage. Data were transferred to a personal com-

Table 1 Clinical details of acute stroke patients

Patient	Gender	Age (years)	Onset of symptoms (days)	Affected hand (hand dominance)	Stroke localisation	Hand paresis	Tactile sensibility	Proprioception	NIH Stroke Scale
R. N.	M	62	10	R (R)	Med. obl.	2	1	1	11
R. W.	W	70	12	L (R)	P, C. r.	1	2	1	7
R. T.	W	70	7	R (R)	P, C. r.	1	2	2	8
T. S.	W	74	2	L (R)	P, C. r., T	1	1	1	7
S. M.	M	75	3	R (R)	P, C. r., BG	2	2	1	6
L. L.	W	81	7	L (R)	BG, Th	2	1	2	9
E. S.	M	62	10	L (R)	C. i., Th	2	2	2	9
R. H.	M	59	7	R (R)	BG, Th, C. e.	2	2	2	8
F.Ö.	M	64	5	R (R)	BG, C. r.	1	1	1	3
E. M.	W	48	10	L (R)	P	2	2	2	10
T. R.	M	53	4	R (L)	P, O	1	2	1	5

Handiness: R = right; L = left. *Stroke localisation:* Med. obl. = medulla oblongata; P = parietal cortex; T = temporal cortex; O = occipital cortex; C. r. = corona radiata; BG = basal ganglia; Th = thalamus; C. i. = Capsula interna; C. e. = Capsula externa. *Hand paresis:* 0 = no, 1 = slight, 2 = moderate, 3 = severe paresis. *Tactile sensibility:* 0 = no, 1 = slight, 2 = moderate, 3 = severe deficit (pressure sensitivity and two-point discrimination of thumb and index finger). *Proprioception:* 0 = no, 1 = slight, 2 = moderate, 3 = severe deficit (contralateral reproduction of passive finger and hand movements). NIH Stroke Scale = National Institute of Health Stroke Scale [4]

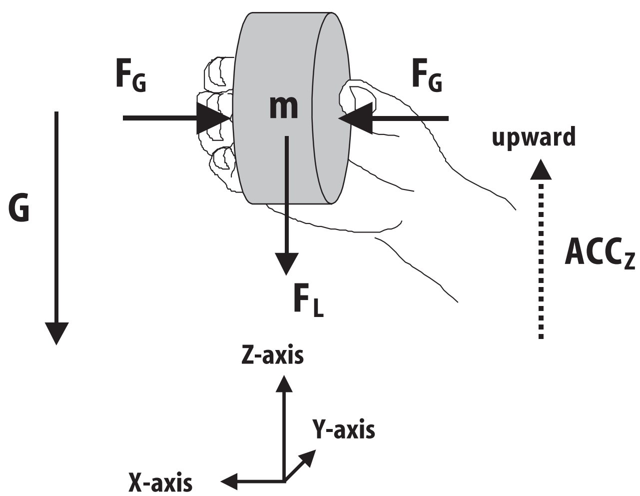

Fig. 1 Instrumented object, configuration of the hand and fingers used to grasp it, and forces produced during an upward movement. The object incorporated a force sensor to register grip force and three linear acceleration sensors to measure kinematic and gravitational accelerations in three dimensions (X-, Y- and Z-axes). m = mass (0.35 kg); G = gravity; ACC_z = kinematic acceleration in the direction of movement; F_G = grip force; F_L = load force. The load force was calculated from the product of the object's mass and the vectorial summation of gravity and kinematic accelerations along the object's Y- and Z-axis ($F_L = m \times \sqrt{ACC_y^2 + (ACC_z + G)^2}$)

puter for analysis following each experimental setting with a single subject.

Procedures

All patients and control subjects were investigated on both hands. In the patients, each task was first tested on the hand ipsilateral to the lesion, assuring that patients were already confident with the task when the affected hand was examined. In an alternating manner one half of the control subjects started the tests with the left hand and the other half with the right hand. Post-hoc analysis assured that there were no effects of sequence.

Lifting and holding the object

First the lifting tasks were performed (see Fig. 2A). Prior to the experiments the subjects washed their hands with soap and water and dried them. The subjects sat in a chair in front of a table with their dominant upper arm parallel to the trunk, and with their unsupported forearm extending anteriorly. In this position, they were asked to grasp and lift the manipulandum, which was placed on the table before them (Fig. 1). The lifting movement took place mainly by flexion of the elbow joint. During the lifting trials the manipulandum was lifted to about 20 cm above the table, held in this position for 15 s, and then replaced and released. The lifting amplitude was specified by simply holding a ruler beside the lifting hand. Each subject carried out five such trials with inter-trial intervals of 10 to 20 s. Before the experiments the subjects received verbal instructions from an experimenter, who also performed a demonstration trial. At the end of the fourth and fifth lifting trial, subjects were asked to slowly separate the thumb and other fingers until the manipulandum was dropped. This procedure was carried out to obtain an estimate of the minimal grip force (slip force) necessary to prevent the manipulandum from slipping. The slip point was defined as the first detectable change in acceleration along the object's vertical Z-axis and the minimum grip force was determined at this time point. The difference between the grip force applied by the subject during stationary holding the object and the minimum grip force is considered a safety margin (compare [23]).

Vertical point-to-point arm movements with the hand-held object

Secondly, the point-to-point movements were performed (see Fig. 2B). Subjects held the manipulandum in front of the trunk while being seated (Fig. 1). The grip surfaces were oriented vertically and in parallel to the trunk. Prior to the experiments the subjects again washed their hands with water and soap and dried them. Subjects were instructed to move the grasped manipulandum up and down in a straight vertical line and to keep its orientation constant during the movements. In particular, short breaks of approximately one second duration should be introduced in between single upward and downward movements (discrete movements; compare [11]). The movement amplitude should be approximately 30 cm and was specified by

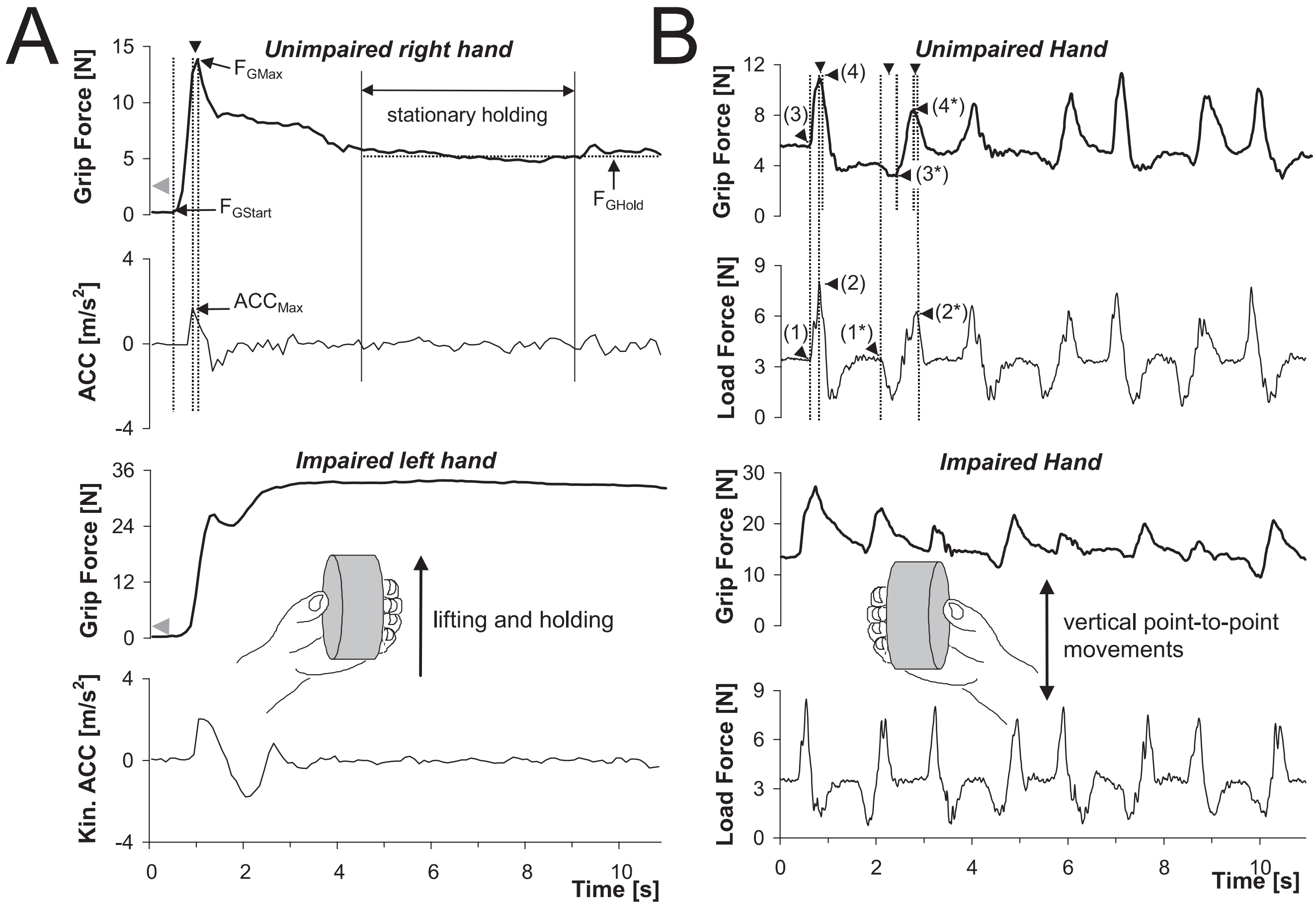

Fig. 2 (**A**) Lifting movements of patient *E.S.* performed with the unimpaired right hand (top panels) and the impaired left hand (bottom panels). The dotted vertical lines indicate the grip force onset (F_{GStart}) and the time lag between maximum grip force (F_{GMax}) and maximum acceleration (ACC_{Max}). The stationary grip force (F_{GHold}) was averaged from a 5 s interval of stationary holding the object and is illustrated by the horizontal dotted line. The time interval used to determine the static grip force was defined to commence definitely after acceleration from the lifting movement has returned to baseline. The minimum grip forces necessary to prevent the object from slipping (slip forces) obtained from the slipping experiments are indicated by gray arrowheads in the grip force panels. (**B**) Grip force and load force profiles obtained from successive vertical arm movements with the hand-held object performed by patient *T. R.* with the unimpaired left (top panels) and the impaired right hand (bottom panels). The dotted vertical lines and arrowheads indicate single time points within the movement course of an upward and downward (*) movement on which data analysis was focused: (1) movement onset, (2) maximum load force, grip force onset (3) and maximum grip force (4). Arrowheads on the top of the dotted vertical lines indicate the time lags between maximum load force and maximum grip force during the upward movement and the time lag between movement onset and onset of grip force during the downward movement. Note the different scaling in the grip force panels in (A) and (B)

holding a ruler beside the moving hand during the first movements of each subject. Subjects were told to perform movements at a fast to moderate speed, but were not paced during performance. The experimenter carried out a demonstration trial prior to the experiments and monitored the subjects visually during the experiments to ensure that they complied with these instructions. The movements were largely achieved by rotations of the upper arm about the shoulder joint. Small rotations about the elbow and wrist were required to preserve the orientation of the manipulandum. Five trials with eight to ten discrete vertical movements were performed by each patient and control subject. The pause between trials amounted to 20–30 s.

Data processing

Lifting and holding the object

Positive kinematic acceleration along the object's Z-axis was directed upward. The total acceleration was a combination of gravity (9.81 m/s^2) and the kinematic acceleration produced during the lift. The net load force (F_L) was calculated from the product of the object's mass and the total accelerations along the object's Y- and Z-axes (see Fig. 1). This method included additional inertial loads, which arose from movement components in the transversal (Y-) direction. Loading components acting in the direction of the applied grip forces (X-axis, compare Fig. 1) were not included in the calculation of the object's net load. These loads, acting orthogonal to gravity and kinematic acceleration of the object, did not need to be compensated by prehensile finger forces to prevent the object from slipping. The general structure of the lifting trial is illustrated for the performance of patient E. S. with the unimpaired right (top panels) and impaired left hand (bottom panels) in Fig. 2A. During a lifting trial the object was gripped, lifted from the supporting table and held in the air for 15 s. The measured grip force and kinematic acceleration and the calculated load force curves (not illustrated in Fig. 2A) obtained from the lifts yielded a series of parameters included in the data analysis: (1) maximum acceleration of the lifting movement (ACC_{Max}), (2) peak grip force magnitude (F_{GMax}), (3) time to reach maximum grip force (TF_{GMax}), (4) time between grip force onset and acceleration onset (TF_{GStart}–$TACC_{Start}$), (5) time between maximum grip force and maximum acceleration (TF_{GMax}–$TACC_{Max}$), (6) ratio between maximum grip and load force (F_{GMax}/F_{LMax}), (7) static grip force (F_{GHold}) adopted while holding the manipulandum steady above the table. The static grip force was calculated from the average grip force produced during a 5 s interval of stationary holding the manipulandum, which was defined to start after the acceleration changes from the lifting movement had returned to baseline indicating the absence of movement (see top panel of Fig. 2A).

The time to reach maximum grip force (TF_{GMax}) provides information about the rate of grip force development at the grasping digits. The time between grip force onset and acceleration onset (TF_{GStart}–$TACC_{Start}$) can be considered a measure of the coordination between the grasping fingers and more proximal arm muscles engaged in the vertical lifting of the object. The time between maximum grip force and maximum acceleration (TF_{GMax}–$TACC_{Max}$), which coincided with the time point of maximum load force, is considered to be a measure for the temporal accuracy of anticipatory grip force adjustment to the load force induced by the voluntary lifting movement. The maximum grip force (F_{GMax}) and the ratio between maximum grip and load force (F_{GMax}/F_{LMax}) provide information about the automatic process of grip force scaling from memories of sensory-motor sets matched to object properties, such as the object's weight and surface friction. The static grip force established during stationary holding of the manipulandum is the result of grip force adaptation to the obtained object properties by actual sensory feedback information.

Vertical point-to-point arm movements

The grip force and acceleration traces obtained from consecutive vertical point-to-point movements performed by patient T. R. with the unimpaired left (top panels) and the impaired right hand (bottom panels) are illustrated in Fig. 2B. Pure kinematic acceleration in the direction of movement (ACC) is illustrated in Fig. 2B and was calculated by subtracting gravitational acceleration from the total acceleration measured. The net load force (F_L) was calculated from the object's mass and the vectorial summation of accelerations parallel to the grip surface, including gravity and inertial accelerations along the object's Y- and Z-axes (see Fig. 1).

Four time points within the movement course were determined. In Fig. 2B, these time points are illustrated in the grip force and load force traces for an upward and a downward movement (*) performed by subject T.R. with the unimpaired hand (top panels): (1) movement start determined from a change in the acceleration signal (not illustrated in Fig. 2B), (2) maximum load force (F_{LMax}), (3) onset of grip force increase (F_{GStart}) and (4) maximum grip force (F_{GMax}). At these time points grip force and acceleration signals, as well as calculated absolute load force were determined. The maximum load force (F_{LMax}) coincided with the maximum of kinematic acceleration (ACC_{Max}) (upward acceleration peak and downward deceleration peak).

The ratio of maximum grip force to maximum load force (F_{GMax}/F_{LMax}) at the time of maximum kinematic acceleration was used to relate the magnitudes of the two forces directly. During vertical movements, this force ratio is considered to be a highly sensitive measure of the economy of produced grip force in relation to the load force. The temporal coupling between grip force onset and acceleration onset was assessed by calculating the time lag between grip force onset and the start of arm acceleration (TF_{GStart}–$TACC_{Start}$). The time lag between maximum grip force and maximum load force (TF_{GMax}–TF_{LMax}) was calculated to analyse the temporal relation between grip and load forces.

Statistical analysis

To control for the effects of handiness, each patient was age-matched with a control subject and the affected hand of the patient was matched with the left or right hand of the control subject according to hand dominance. For example, if the right hand was affected in a right-handed patient, it was matched with the right hand of a right-handed control subject. Here we present results of the comparative analysis between the performance of the hand of the patients contralateral to the lesion and the performance of the matched hand of the control subjects.

Data of single trials belonging to one task were averaged for each participant. The performance of the affected patient hand and dominance-matched control hand were compared using t tests for independent variables. A P value of 0.05 was considered statistically significant. Means and standard deviations are reported.

Results

Lifting and holding the object

All participants were able to grasp the instrumented object, lift it to the required height, and hold it stable in the air. Fig. 2A illustrates the performance of patient E.S. when grasping, lifting and holding the object with the unimpaired and the affected hand. The individual phases of the lifting movement were previously described in detail by Johansson, Westling and colleagues [23]. The dotted vertical lines in the grip force and acceleration traces illustrate individual time points within the movement course on which data analysis was focused. After the fingers made contact with the object (F_{GStart}), grip force started to increase. When grip force had overcome the object's inertia, the object started to move upward and the acceleration increased. A maximum of grip force (F_{GMax}) occurred closely in time with maximum upward acceleration.

During the phase of stationary holding, indicated by the two solid vertical lines in the grip force and acceleration traces for the lift with the unimpaired hand, the acceleration values demonstrate the absence of relevant movements. The average grip force established during the phase of stationary holding (F_{GHold}) is indicated by the dotted horizontal line for the lift with the unimpaired hand. The maximum grip force was clearly smaller for the lift with the unimpaired hand than the lift with the impaired hand. While the grip force established by the unimpaired hand during stationary holding the object reached values around 6 N, the impaired hand produced markedly elevated grip forces around 35 N. A particular interesting finding in this patient is the gradual increase of the grip force level following the occurrence of maximum grip force during the lift with the impaired hand, whereas the grip force level decreased following the occurrence of maximum grip force during the lift with the unimpaired hand. All patients exhibited increased grip forces on the hand contralateral to the brain lesion. The described qualitative findings were similar for the lifting movements of all stroke patients.

Coupling between grip and load force magnitudes

The individual minimum grip forces required to prevent the object from slipping as obtained from the slip experiments (see Methods) are indicated by arrowheads in the grip force panels of Fig. 2A for the lifts with both hands. The minimum grip forces for the impaired patient hands (2.2 ± 0.4N) and the matched control hands (2.5 ± 0.3N) were similar (P > 0.1).

Fig. 3A presents group means and standard deviations of maximum upward acceleration, maximum grip force, the ratio between maximum grip and load forces and static grip force established when the object was held stationary for the group of healthy controls and stroke patients. The maximum upward acceleration (ACC_{Max}) of the lifting movement was similar for controls and patients (top panel in Fig. 3A). The maximum load force occurred at the time of maximum upward acceleration (see Methods). The values of maximum load force (not illustrated in Fig. 3A) reflected the findings for the values of maximum acceleration on which they depended. The maximally produced grip forces (F_{GMax}) were significantly greater for the impaired hand of patients than for the hand dominance-matched hand of the controls (second panel from top in Fig. 3A).

Accordingly, the ratios between maximum grip and load forces (F_{GMax}/F_{LMax}) were significantly greater for patients than for controls. As the force ratio between maximum grip and load forces is considered a highly sensitive measure for the economy of the produced grip forces, all impaired patient hands produced uneconomically elevated grip forces in relation to the actual loading requirements. Also the grip forces established against the hand-held object during the phase of stationary holding (F_{GHold}) were significantly greater for the patients' impaired hands when compared with the matched control hands (bottom panel in Fig. 3A). We observed no significant differences of the analysed force

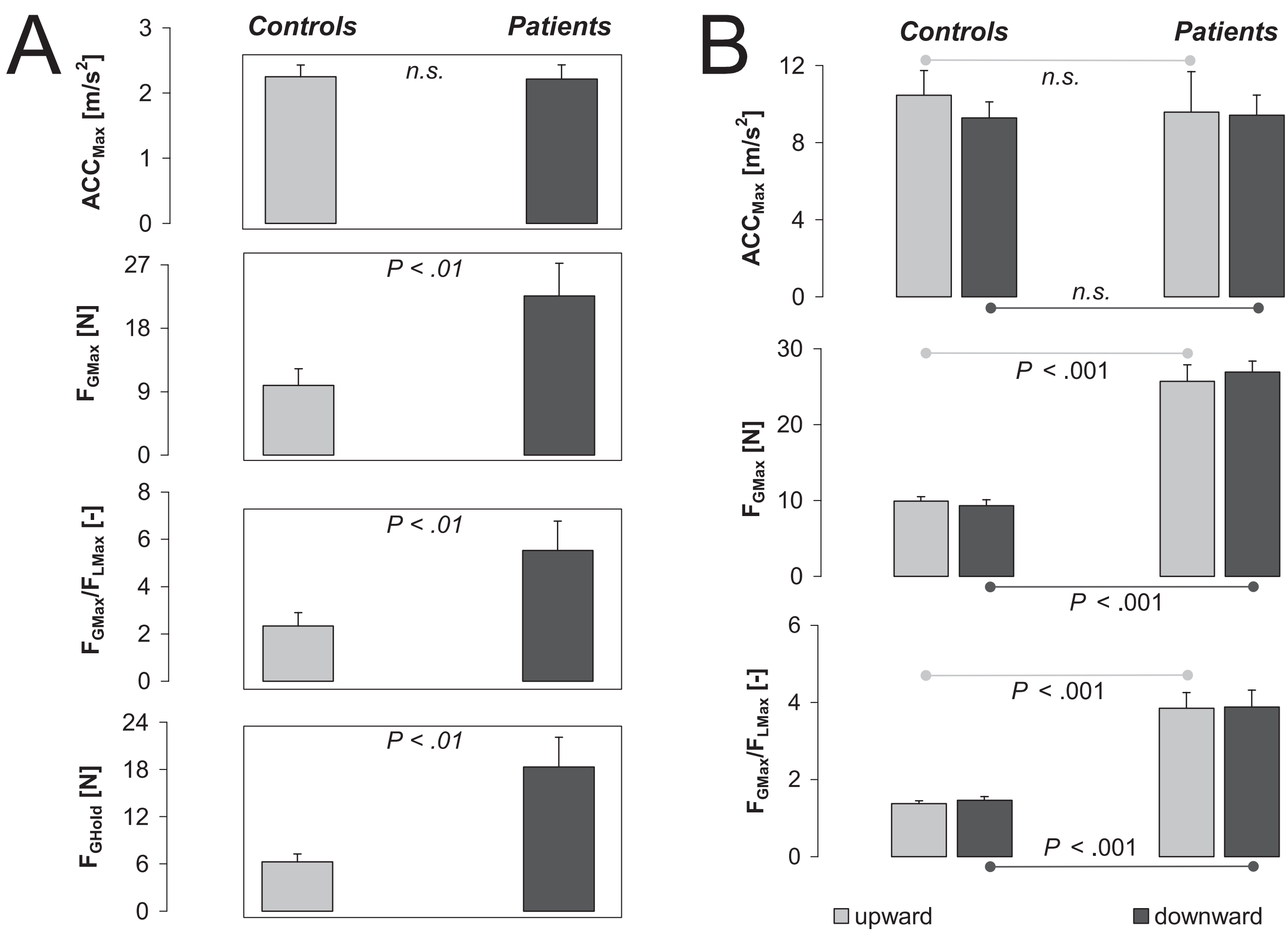

Fig. 3 (**A**) Means and standard deviations of maximum acceleration of the lifting movement (ACC_{Max}), maximum grip force (F_{GMax}), ratio between maximum grip force and maximum load force (F_{GMax}/F_{LMax}) and static grip force established against the hand-held object (F_{GHold}) during the phase of stationary holding are illustrated for healthy controls and stroke patients. (**B**) Means and standard deviations of maximum acceleration (ACC_{Max}), maximum grip force (F_{GMax}) and the ratio between maximum grip force and maximum load force (F_{GMax}/F_{LMax}) during upward and downward point-to-point movements performed by healthy control subjects and stroke patients

scaling parameters within the group of patients and the group of control subjects.

Temporal coupling between grip and load force profiles

In Table 2 the time to reach maximum grip force (TF_{GMax}) and the time lag between maximum grip force and maximum acceleration (TF_{GMax}–$TACC_{Max}$) are summarised for patients and healthy controls. The time to reach maximum grip force relative to the onset of grip force increase provides information about the rate of force development at the grasping digits. When patients performed the lifting task with the impaired hand, the time to reach maximum grip force was significantly prolonged if compared with the performance of the matched hand of the control subjects ($P < 0.01$). The time lag between grip force onset and acceleration onset provides information about the coordination of more proximal arm muscles engaged in the lifting movement and distal finger muscles stabilising the grasp. The time lag between grip force and acceleration onset was significantly longer for patients than for controls ($P < 0.05$). The time lag between maximum grip force and maximum lifting acceleration contains information about the temporal coupling between grip and acceleration profiles. In healthy controls, maximum grip force coincided with maximum acceleration of the lifting movement. Compared with healthy controls, maximum grip force significantly lagged behind maximum upward acceleration for the lifting movements performed by the stroke patients ($P < 0.05$).

Vertical point-to-point movements with the hand-held object

Fig. 2B illustrates the grip and load force profiles of patient T.R. during consecutive vertical point-to-point movements with the hand-held object performed with the unimpaired and the impaired hand. The dotted vertical lines within the grip and load force profiles indicate individual time points within the movement course at which data analysis was focused. The general structure of vertical point-to-point movements and the qualitative coupling between grip and load force profiles have been described in detail by Flanagan and Wing [11]. A maximum in load force occurred at the onset of upward and near the end of downward movements. During movements with the impaired and the unaffected hand grip force increased early in upward movements and late in downward movements and a maximum of grip force coincided closely in time with the maximum of load force regardless of movement direction. Thus, the general structure of the grip and load force coupling was retained for movements in both vertical directions performed with the impaired hand for all stroke patients. However, it is evident that the grip force profile is modulated at higher force levels during vertical point-to-point movements with the impaired hand. The qualitative observations described for the coordination between grip and load force profiles were similar for all stroke patients.

Coupling between grip and load force magnitudes

In Fig. 3B means and standard deviations of maximum accelerations (ACC_{Max}), maximum grip forces (F_{GMax}) and the ratios between maximum grip and load forces (F_{GMax}/F_{LMax}) produced during upward and downward movements are illustrated for control subjects and stroke patients. The maximum accelerations were similar for patients and controls regardless of movement direction. The maximum load forces (not illustrated in Fig. 3B) reflected the observations for the maximum accelerations on which they depended. The maximally produced grip forces were significantly greater for patients than for controls regardless of movement direction, despite similar maximum loads resulting from the arm movements. Consequently, the ratios between maximum grip and load forces were significantly greater for movements produced by patients regardless of the direction of movement. Similar to the lifting movements,

Table 2 Means and standard deviations (in parenthesis) of the time to reach maximum grip force (TF_{GMax}), the time lag between grip force onset and acceleration onset (TF_{GStart} – $TACC_{Start}$) and the time lag between maximum grip and load forces (TF_{GMax} – $TACC_{Max}$) for the lifting movement and the time lags between grip force onset and onset of acceleration (TF_{GStart} – $TACC_{Start}$) and between maximum grip and load forces (TF_{GMax} – $TACC_{Max}$) for the vertical point-to-point movements are illustrated. A positive time lag indicates that grip force onset (maximum) lagged behind the onset (maximum) of acceleration. A negative time lag indicates that the grip force started to rise (reached its maximum) prior to the onset (maximum) of acceleration

	Lifting movements			Point-to-point movements		
	TF_{GMax} [ms]	Time Lag TF_{GStart} – $TACC_{Start}$ [ms]	Time Lag TF_{GMax} – $TACC_{Max}$ [ms]	Movement Direction	Time Lag TF_{GStart} – $TACC_{Start}$ [ms]	Time Lag TF_{GMax} – $TACC_{Max}$ [ms]
Patients	413.1 (46.1)	261.9 (51.3)	33.8 (49.5)	up	17.4 (47.4)	12.1 (11.0)
				down	136.3 (38.5)	–1.8 (17.1)
Controls	268.7 (32.1)	125.6 (54.2)	3.5 (13.8)	up	0.9 (14.1)	8.6 (6.6)
				down	254.8 (50.7)	–1.8 (9.5)

stroke patients established markedly elevated grip forces against the hand-held object during the stationary holding phases of the vertical point-to-point movements. We found no significant differences of the analysed force scaling parameters within the group of patients and the group of control subjects.

Temporal coupling between grip and load force profiles

In Table 2 the time lags between grip force onset and acceleration onset (TF_{GStart}–$TACC_{Start}$) and between maximum grip forces and maximum accelerations (and thus maximum load forces) (TF_{GMax}–$TACC_{Max}$) are illustrated for upward and downward movements performed by patients and control subjects. Flanagan and Wing demonstrated that the grip force of healthy subjects started to rise with the onset of acceleration in upward movements and late during the movement course (close to the onset of deceleration) in downward movements (Flanagan and Wing, 1993, see their Fig. 2) [11]. Consequently, in healthy subjects the time lag between grip force onset and acceleration onset is small for upward and large for downward movements. We observed a similar relation between the onset of grip force rise and the onset of acceleration in the vertical point-to-point movements performed by healthy controls and stroke patients. However, compared with healthy controls the time lag between the onset of grip force and the onset of acceleration was larger for upward and smaller for downward movements performed by stroke patients (upward: $P < 0.01$; downward: $P < 0.03$). This finding suggests a less precise differentiation between upward and downward movements when predictive grip force adjustments were computed according to expected load fluctuations in stroke patients.

In healthy subjects, the time lag between maximum grip force and maximum acceleration is commonly very small, indicating that maximum grip force coincided with maximum acceleration during both upward and downward point-to-point movements [11]. We observed similar small time lags between maximum grip force and maximum acceleration for healthy controls and patients. Thus, the maximum grip force produced by stroke patients anticipated the maximum acceleration with similar precision regardless of movement direction.

Discussion

In the present study, we analysed grip force control in acute stroke patients with mild to moderate sensory and motor impairments of the hand contralateral to the lesion. Two major components of grip force control were examined: the economical scaling of grip forces according to the actual loading requirements of the movement and the temporal coupling between grip and load force profiles. Interestingly, we observed a dissociation of performance deficits in acute stroke patients with major impairments of the accurate grip force scaling in relation to the loads and selective impairments of the temporal regulation of the grip force profile with the load profile.

Impairments of economical grip force scaling

Stroke patients produced markedly increased grip forces when lifting and holding the object and when performing vertical point-to-point movements with the hand-held object. In healthy subjects, grip forces are usually only a small amount higher than the minimum required to prevent a grasped object from slipping [21, 23]. The excessively high grip forces employed by our stroke patients may hamper fine finger movements resulting in severe deficits of manual activities of daily life [18, 29]. The reduction of unnecessarily elevated grip forces during manipulative tasks might therefore become a central issue of rehabilitation in stroke patients with mild to moderate motor impairments of the hand.

Uneconomically elevated grip forces during manipulation of hand-held objects have been documented in a variety of pathological conditions, such as impairments of afferent manual sensibility [41, 42], cerebellar dysfunction [9, 33], motor neuron disease [34] and basal ganglia disorders [10, 38], and may therefore be considered a quite general control strategy when the sensorimotor system is functionally impaired. Recently, we attributed the grip force increase observed in patients with chronic cerebral lesions to deficient sensorimotor integration due to impaired manual sensibility during a grasp perturbation task [17]. A constant precision grip between the index finger and thumb was perturbed by an externally produced load increase that suddenly displaced the fingers until a reactive grip adjustment occurred that stopped and reversed the displacement. The amount of displacement correlated with the amount of sensibility loss of the grasping fingers. A predominant role of tactile afferent input from the grasping digits for accurate grip force scaling has also been suggested by experiments involving microneurographic recordings from peripheral sensory nerves [23] or cutaneous anesthesia of the grasping digits [22, 23, 32]. In the present study, all patients exhibited sensory deficits of the impaired hand that were uniformly mild to moderate.

Interestingly, patients with impaired manual sensibility due to chronic median nerve compression were able to adjust grip forces in a highly economical way according to the movement-induced loads during a lifting task [42]. This observation suggests that patients with peripheral nerve dysfunction are able to compensate for their sensory deficits, whereas patients with manual sensory impairments of central origin can not automatically compensate for the disabling effects on grip force control even when the deficits are moderate. Our patients always performed the tasks initially with the unimpaired hand, but this experience was obviously not sufficient to accurately scale the grip forces according to the actual loading requirements when performing with the affected hand. In the patient group, the increase of the established grip force may also be considered a motor strategy to compensate for accidental perturbations of the object loading due to insecurities in the performance of the movement. The average ratio between maximum grip and load forces established by stroke patients was approximately 100 % higher during the lifting task and approximately 120 % higher during the point-to-point movement task when compared with the ratios produced by controls. As all patients were able to perform the lifting and movement tasks without relevant disturbances, the greater force ratios may still be considered unnecessarily high, even when more irregular arm movements were taken into account.

Impairments of the temporal coupling between grip and load force profiles

When an object is grasped and lifted from a support, the time to reach maximum grip force, relative to the time the fingers made contact to the object surfaces, provides information about the rate of force development. The time to reach maximum grip force was significantly prolonged in acute stroke patients compared with healthy controls. Prolongation of this time interval can partially be attributed to the extra time required to reach the abnormally high grip forces in the stroke patients. However, we also observed prolongation of the time between grip force onset and acceleration onset, which provides information about the coordination between muscle commands to the distal finger muscles grasping the object and more proximal arm muscles engaged in the actual lifting movement. We therefore assume that stroke patients had problems in the motor coordination between finger and arm muscles and needed more time to establish a secure grip and to get the object in motion. In addition, we found the time lag between maximum grip force and maximum acceleration to be significantly longer in stroke patients than in healthy controls. This interval is an important measure with which to assess the precision of the anticipatory timing of the grip force maximum to coincide with the load force maximum. Thus, stroke patients revealed impairments in the precise anticipatory coupling between grip and load force profiles when lifting an object with the affected hand.

Prolongation of the times between the onset of grip force and the onset of acceleration (time to get the object in motion) and the time to reach maximum grip force was previously described in Parkinsonian patients [10], elderly persons [5] and in cerebellar patients [9] performing a lifting task. In the case of Parkinsonian subjects and in older persons a marked slowing of the grip force development at the grasping digits due to impaired sensorimotor integration of afferent feedback signals, which in turn delays subsequent force adjustment phases during the grip-lift synergy, was suggested [5, 10]. In addition, we found similar timing deficits during a transport task in patients with chronic cerebral lesions [17] who exhibited similar sensory and motor deficits of the affected hand as observed in the present group of acute stroke patients indicating that impaired sensorimotor integration of afferent feedback signals may result in profound disturbances of predictive grip force regulation.

It is important to note that prolongation of temporal measures obtained from the phases of grasping and lifting the object do not appear to indicate a breakdown of the normally very close temporal grip – load force coupling. Indeed, stroke patients in principal retained temporal aspects of the coupling between grip and load force profiles when performing vertical point-to-point movements with the hand-held object. In particular, grip force increased early in upward and later in the course of downward movements. Nevertheless, we observed larger time intervals between the onset of grip force and the onset of acceleration for upward and smaller such time intervals for downward movements performed by patients compared with controls. From this observation we suggest that the predictive regulation of grip forces in stroke patients revealed a less precise differentiation between the individual loading requirements for upward and downward movements. However, maximum grip and load forces coincided very closely in time during vertical point-to-point movements performed by stroke patients, indicating that for this event the motor commands for grip force adjustments were precisely coordinated with the arm movement commands responsible for the object loading.

The close temporal coupling between grip and load force profiles during dynamic object manipulations was interpreted as evidence for the existence of an internal forward model that predicts the consequences of our own motor actions and its implication on the loading of a grasped object [2, 12, 43–45]. Recently, we found uneconomically elevated grip forces in conjunction with a precise temporal coupling between grip and load force profiles in healthy subjects performing vertical point-to-point movements with a hand-held with anesthetised grasping fingers [32]. The current results provide further support to the notion that the scaling of the grip force magnitude and the temporal regulation of the grip force profile are dissociable aspects of force control.

Internal neural representation of anticipatory grip force control

The stroke patients participating in the current study experienced a single cerebrovascular accident. The lesion included the cortical grey and underlying white matter, the thalamus, the basal ganglia, and the external and internal capsula. One patient suffered from a brainstem ischemia. Interestingly, we observed similar deficits in the scaling of grip force magnitude and in the temporal coupling between grip and load force profiles in our inhomogeneous group of acute stroke patients. Single cell recordings, functional imaging and anatomical studies have demonstrated that a widespread network of cortical and sub-cortical regions are engaged in regulating finger forces during precision grip tasks [7, 16, 26, 27, 36, 40].

It has been suggested that the cerebellum incorporates an internal forward model responsible for the precise regulation of grip forces in anticipation of movement-induced load fluctuations of a manipulated object [44, 45]. Our observations suggest that cortical and subcortical sensorimotor structures may be involved in subsequent processing of motor commands for anticipatory grip force adjustments. For example, cerebral sensorimotor areas are engaged in adjusting the grip force level in an economical way according to the actual physical object properties [7, 30, 36]. The grip force profile is further tuned and precisely adjusted according to the loads predicted from preceding object manipulation or according to the actual loads resulting from voluntary movements of a hand-held object. Thus, cerebral sensorimotor structures are involved in the monitoring of afferent feedback signals and in the triggering of motor output according to external perturbations [15, 27, 39].

In conclusion, impairment of grip force control is an essential feature of impaired motor performance of the affected hand in acute stroke patients. In particular, we found markedly elevated grip forces which may facilitate early fatigue of hand muscles, reduce the ability to perform very fine manipulations of grasped objects and may therefore contribute to a greater level of disability in activities of daily living. Deficits of economical grip force scaling probably result from impaired sensorimotor integration. There were only slight disturbances of the precise temporal coupling between grip and load force profiles, indicating that the general features of forward force control in anticipation of movement-induced load fluctuations were preserved. The grip force paradigm provides a useful tool to measure impairments of manual performance in stroke patients.

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