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THE FUNCTIONAL VALUE OF ELECTRICAL MUSCLE STIMULATION FOR THE REHABILITATION OF THE HAND IN STROKE PATIENTS

Horst Hummelsheim, Maria Lucia Maier-Loth and Christel Eickhof

From the Klinik BERLIN, Department of Neurological Rehabilitation, Free University of Berlin, Berlin, FRG

ABSTRACT. The influence of suprathreshold electrical stimulation of the extensor and flexor carpi radialis muscles on biomechanical and functional movement parameters is compared with the effect of a standardized active repetitive training of hand and fingers. Twelve patients suffering from ischaemic lesions in the territory of the middle cerebral artery participated in the study, which was conducted using a multiple baseline design. Following a baseline phase that lasted between one and three weeks all patients received electrical muscle stimulation for 20 minutes twice daily. In a third phase the repetitive training of hand and fingers was conducted for 20 minutes twice daily. Both interventions were applied in addition to conventional occupational therapy and physiotherapy. With the exception of spasticity in hand and finger flexors, repetitive electrical muscle stimulation does not improve biomechanical or functional motor parameters of the centrally paretic hand and arm. The repetitive motor training, however, is appropriate to improve biomechanical and functional movement parameters significantly. Apart from a possible effect on the muscle cell itself, the electrical muscle stimulation is thought to represent a mainly sensory, i.e. proprioceptive, and cutaneous intervention, whereas the active motor training is characterized by a continuous sensorimotor coupling within motor centres of the brain. The underlying neurophysiological mechanisms as well as basic principles concerning the role of afferent input for motor learning and recovery are discussed.

Key words: afferent input, electrical stimulation, hand function, motor learning, movement repetition, stroke patients.

INTRODUCTION

Although crucial for social and vocational rehabilitation, functional recovery of the stroke patient's paretic hand proves to be reluctant and unsatisfactory in many cases. In recent years, special physical approaches exercise have been designed to improve the outcome of motor rehabilitation of centrally paretic distal arm and hand (1, 8, 16, 21, 27, 34).

The physiotherapeutic methods according to Affolter (1) and Perfetti (27) consider the importance of perceptual and attentional processes for the acquisition of motor skills and for recovery from motor deficits. The particular relevance of afferent feedback information during active and passive movements is particularly emphasized. Unfortunately, there is still a lack of prospective studies dealing with the functional value of these approaches.

A standardized repetitive motor training of centrally paretic muscle groups of the hand has been developed to improve functional motor capacity of hand and arm in stroke patients (8). Similar positive results were observed when EMG-initiated electrical muscle stimulation was repetitively applied to the hand extensors and flexors (16, 21). The common feature of both training procedures is the repetitive voluntary activation of functionally important muscle groups of distal arm and hand. The proprioceptive and cutaneous impulses generated repetitively and time-locked to the unfolding voluntary movement are thought to form the basis of motor learning (3) as well as motor recovery in stroke patients irrespective of whether the repetitive motor training (8) or the EMG-initiated electrical muscle stimulation is still employed (16, 21). Both approaches are appropriate to strengthen the sensorimotor coupling within motor regions of the brain involved in the movement.

During natural movements, input selection and input filtering are thought to reduce the effective excitatory input for neurons in the sensorimotor cortex. Nevertheless, a raised quantity of synchronous neural activity in afferents from circumscribed body regions results in unmasking phenomena (17) within pre-existing but functionally inactive neuronal circuits and therefore in enlarged cortical representational zones (18).

Interestingly, most studies dealing with the reorganization of cortical representational maps (18, 24, 31) are not restricted purely to sensory stimulation but are included in an enhanced motor activity. The same holds true for investigations in humans concerning the influence of an enhanced sensory impulse transmission on motor performance (8, 16, 21).

In the present prospective study, a multiple baseline design is used to investigate the influence of repetitive electrical stimulation of centrally paretic wrist extensor and flexor muscles on biomechanical and functional movement parameters of arm and hand. Apart from a possible effect on the muscular tissue itself (25), the electrical muscle stimulation is regarded as a mainly sensory, i.e. proprioceptive and cutaneous, intervention. The effect of the raised sensory inflow induced by electrical stimulation is compared with the influence of an active repetitive motor training as it was described by Bütefisch et al. (8).

METHODS

Twelve patients (4 women, 8 men, aged between 41 and 80 years, mean age 59.5 years) participated in the study. All suffered from CT-confirmed ischaemic lesions in the territory of the middle cerebral artery 3 weeks to 4 months (mean 7.6 weeks) before admission to the study. A careful neurological and neuropsychological examination was undertaken in each patient. Patients with more than one cerebral lesion, major sensory deficits, complete paralysis of the hand, additional lesions of the peripheral nervous system, communication or emotional disturbances, neglect phenomena or other serious neuropsychological deficits were not included. The scores on the Rivermead Motor Assessment, arm section, are illustrated for all phases of the study in Fig. 2. Muscle tone in hand flexor muscles was assessed for each patient by means of the modified Ashworth scale (Fig. 1).

Experimental protocol

A multiple baseline design across individuals was used to study the effect of repetitive electrical stimulations of the extensor and flexor carpi radialis muscle on the performance of basic biomechanical movement parameters of the hand and on functional motor capacity of arm and hand. Biomechanical recordings to be described later were taken once a week during all phases of the study. During the baseline phase (phase A), which lasted between one and three weeks, and during all other phases of the study, each patient received his or her usual conventional physiotherapy following the Bobath (7) concept (45 minutes daily) supplemented by occupational therapy covering particularly the activities of daily living (individual therapy for at least 3 hours a week, plus up to 2 hours' group therapy, including cooking and fine motor activities).

Following the baseline phase (phase A), all patients received electrical muscle stimulations for 20 minutes twice daily for a two-week period (phase B). Transcutaneous electrical stimulation was applied by means of a commercial stimulation equipment (bentrofit f 12/m 13, Bentronic Corp.) in addition to the conventional occupational and physiotherapy described above. The extensor carpi radialis muscle was stimulated for a period of 15 minutes, the flexor carpi radialis muscle for a period of 5 minutes with an intensity appropriate to produce maximum wrist extension and flexion, respectively. A pair of self-adhesive flexible electrodes (2.5 × 3 cm) was used for stimulating the muscle. Stimulation consisted of monophasic exponential pulses at rates of 75 and 80 Hz and a current intensity of 10 to 80 mA (0.5 ms pulse duration) for 4 to 7 seconds. Current intensity was adjusted to produce maximal extension or flexion at the wrist. During the stimulation sessions 50 to 80 extensions and 20 to 30 flexions with an inter-stimulus interval between 5 and 15 seconds were performed.

During the stimulation sessions, patients were asked to avoid voluntary muscular activation. To ascertain that the electrical muscle stimulation indeed works almost exclusively on the afferent loop and is not preceded or followed by voluntary contractions, the definite relaxation of the extensor and flexor carpi radialis muscles was continuously monitored electromyographically by means of a two-channel digital oscilloscope, i.e. before the electrical stimulation and during the inter-stimulus intervals.

Subsequent to the stimulation phase (phase B), the patients received a standardized training programme (phase C) identical to that described by Bütefisch et al. (8). Grip strength was trained by squeezing two metal bars separated from each other by a variable number of springs. Rapid isotonic wrist extensions were performed against low resistance exerted by weights (0–600 g) attached to the hand dorsum. To enhance peak force of hand extension, weights were increased up to 2 kg. Patients were instructed to perform finger flexion and hand extension against various loads repetitively. The patients movement performances were closely observed and the tone of arm muscles frequently assessed in order to detect the occurrence of undesired associated movements and an increase in muscle tone. At both occasions the training was interrupted for a short period and continued after a sufficient reduction of muscle tone. The training was conducted twice daily for 20 minutes each, additional to usual occupational and physiotherapy. The training phase (phase C) lasted for two weeks.

Movement parameters

Grip strength. Grip strength was measured by means of a digital pinch/grip analyser (Kuck Medizin-Elektronik Corp.) that consisted of two flat padded bars mounted parallel to each other in an adjustable distance. Squeezing these bars allowed registration of force. The patients were comfortably seated in a chair with the paretic arm resting in a plaster support adapted to the patient's individual body height. The grip analyser was placed in front of the patient and the distance between the two bars adjusted in a way that the paretic hand could easily squeeze them. Hand position and distance between the two bars were kept constant for the same patient during the entire series of measurements. Patients were instructed to squeeze the two bars after an acoustic signal "as rapidly and strongly as possible" and then to release them. The force signal was stored for later analysis. From each force record the maximum grip strength (contraction amplitude) was extracted by means of an interactive cursor display.

Rapid isometric hand extension. The paretic arm of the sitting patient was supported by a plaster device with the forearm semipronated and the elbow flexed at 90 degrees. In order to register isometric extensions at the wrist, a metal bar transmitting the extension force on a piezoelectric force transducer (Type 9211, Kistler Instruments Corp.) opposed the hand dorsum. The distance between the metal bar and the processus styloideus ulnae was carefully kept constant for each patient throughout all recording sessions. The patients were asked to extend their hand "as rapidly and strongly as possible" following an acoustic signal and then to release. The force signal was stored and peak force (contraction amplitude) was extracted off-line.

Rapid isotonic hand extension. For analysis of the fastest isotonic hand extensions a piezoelectric accelerometer (Type 708, TEAC Corp.) was taped 3 cm distal to the processus styloideus ulnae on the mid-dorsum of the paretic hand. The accelerometer signal was amplified by an SA-6 amplifier (TEAC Corp.). The hand was closed, leaving the full range of motion at the wrist. Patients were instructed to perform a rapid isotonic extension movement at the wrist as fast as possible after an acoustic signal. Accelerometer signals were stored and peak acceleration was measured off-line.

In each session, 10 recordings of the described movement parameters were taken in each patient. The force and acceleration signals were sampled at a rate of 200 Hz over a 2500 ms period and fed into a commercial data acquisition system (MacLab, World Precision Instruments Corp.) for storage and off-line analysis.

To compare the last biochemical values of one phase with the last values of the preceding phase, the non-parametric Wilcoxon signed rank test was used to test the hypothesis that the distribution of the biomechanical values is the same.

Functional motor and spasticity assessment

The Rivermead Motor Assessment, arm section, was used to score the motor capacity of the upper extremity for each patient (10, 23). It is a widely used technique to measure motor ability in stroke patients. Its arm section covers shoulder, elbow and hand function with and without manipulation of objects. The maximal attainable motor score for the arm is 15. The modified Ashworth scale (4, 33) was used to assess muscle tone in hand flexor muscles. Grade 0 means that muscle tone is not increased, grade 5 means that the hand is continuously held in rigid flexion.

The scores on both scales obtained at the end of the baseline phase were compared with those obtained at the end of the stimulation phase, which in turn were compared with those obtained at the end of the training phase by means of the non-parametric Wilcoxon signed rank test.

RESULTS

Clinical observations, functional motor and spasticity assessment

During the stimulation and during the training phase, a decrease in spasticity and in the frequency of occurrence of undesired associated movements in flexor muscles of hand and fingers was observed. The degree of spasticity during the baseline, the stimulation and the training phases, as assessed for the hand flexors by means of the modified Ashworth scale, is depicted in Fig. 1. It remains stable during the baseline phase and decreases during the course of the stimulation and the training phases.

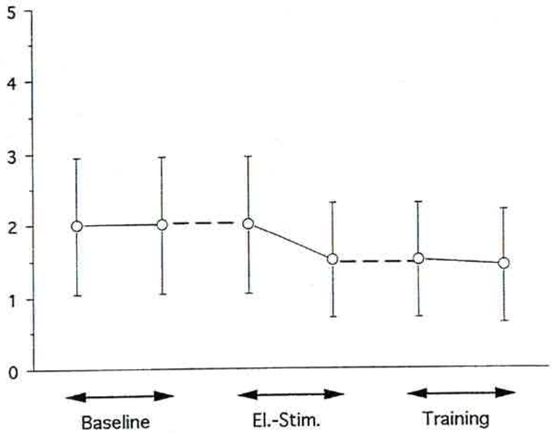

Fig. 1. Muscle tone in hand and finger flexors during all phases of the study as assessed by means of the modified Ashworth scale.

Seven patients experienced a (slight) improvement in their overall motor function of the affected arm as assessed by means of the Rivermead Motor Assessment, arm section, during phase B (Fig. 2). Nevertheless, this improvement was not statistically significant when calculated for the entire patient group. On the other hand, an appreciable and statistically significant ($p < 0.008$) increase in functional motor capacity was observed during the repetitive motor training (phase C). As is depicted in Fig. 2, recovery of arm function (i.e. in proximal and distal motor capacity) starts in most cases when the repetitive training was introduced. During the baseline as well as during the stimulation phase, no statistically significant change in the score on the Rivermead Motor Assessment, arm section, could be detected.

Movement parameters

Figure 3 depicts five superimposed original recordings (patient 10) at the end of the baseline phase, after two weeks of electrical stimulation of hand extensors and flexors and after two weeks of the repetitive training. During baseline and stimulation phases all biomechanical parameters remain stable. As compared to the stimulation phase, an increase

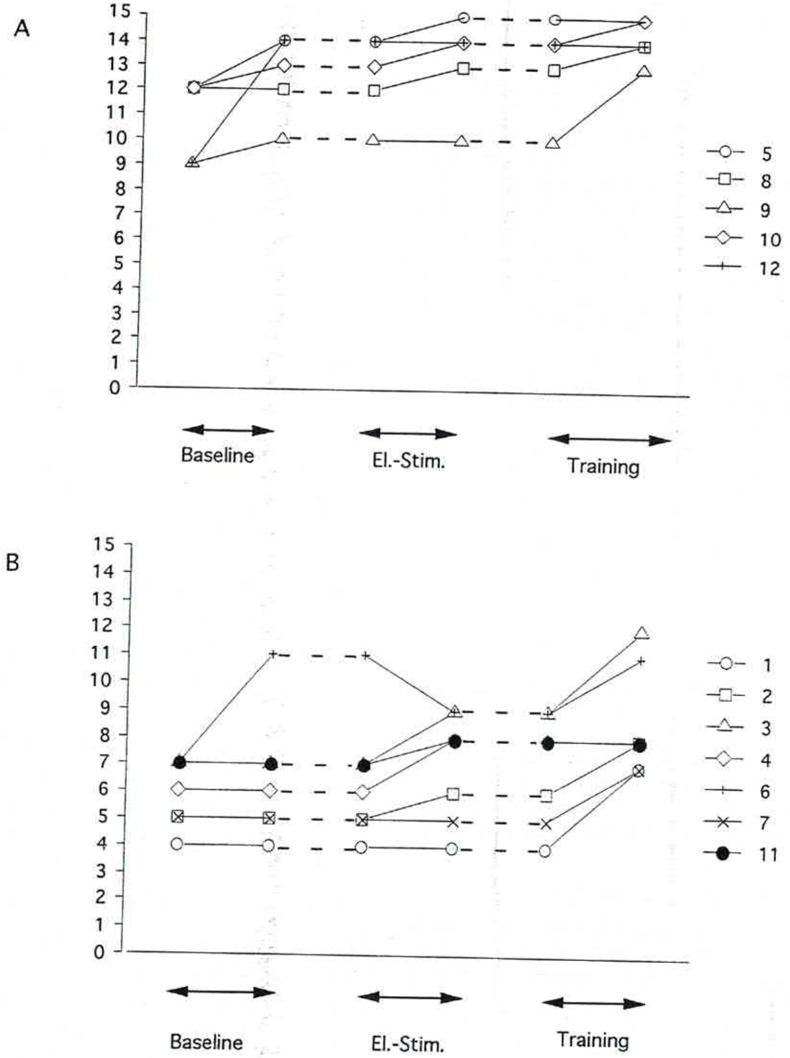

Fig. 2. Functional impairment of the paretic upper extremity as assessed by means of the Rivermead Motor Assessment, arm section. A and B represent different initial degrees of functional impairment. Patient numbers are indicated at the right side.

in grip strength (+95%), peak force (+70%) and peak acceleration (+240%) was achieved until the end of the training phase. Furthermore, the slope of the contraction and acceleration curves prior to their maximum was steeper, indicating an increase in the rate of rise of grip strength as well as contraction velocity and acceleration with increasing amplitudes.

For group comparison during the baseline, the stimulation and the training phases, each patient's maximum grip strength, peak force of isometric and peak acceleration of isotonic hand extensions were calculated weekly relative to his or her last baseline performance (reference value ↓), which was arbitrarily set at zero. Depending on the patients' performance relative to the baseline performance, the score varied equally, below or above zero. During the baseline phase the calculated scores of all movement parameters showed only minor differences in relation to their last baseline value zero (Fig. 4). The lack of visible changes during the baseline and the stimulation phases is confirmed by the Friedman test which indicates that no statistically significant changes occur during these phases. On the other hand, starting with the introduction of the repetitive training a statistically significant increase in all movement parameters (Fig. 4) could be demonstrated (stimulation vs

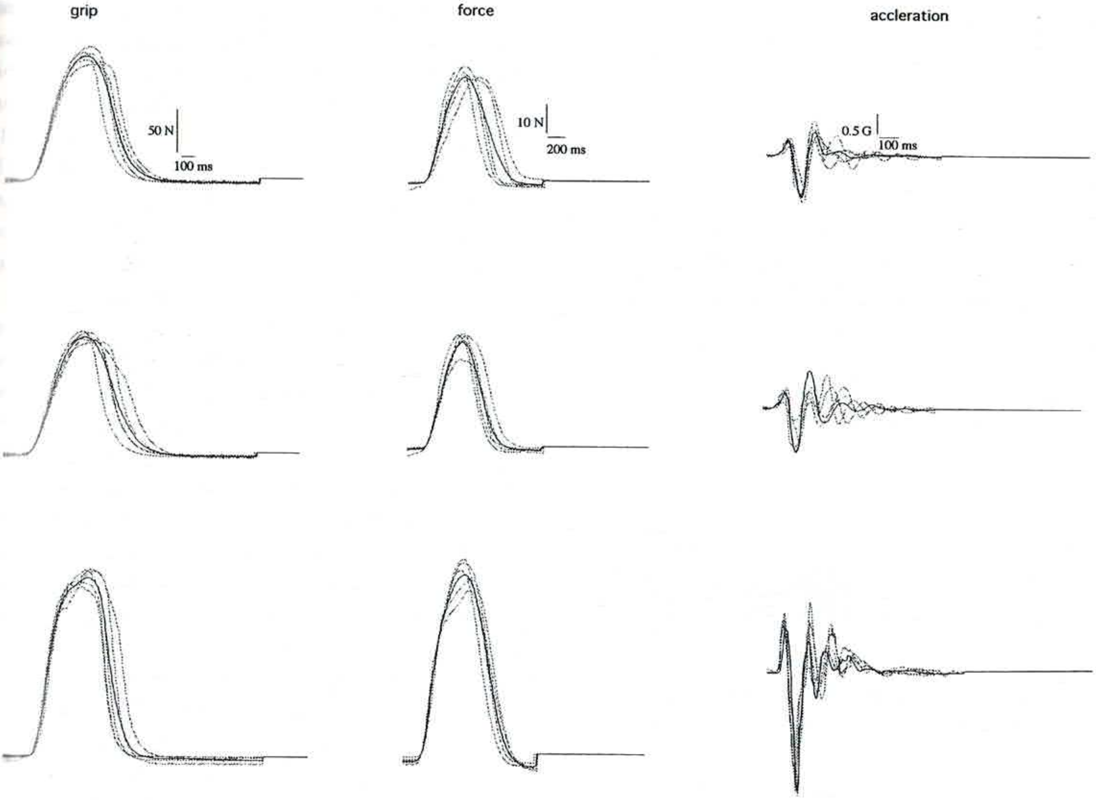

Fig. 3. Five superimposed original recordings (patient 10) of grip strength, maximum force during isometric and maximum acceleration during isotonic hand extension at the end of the baseline phase (upper traces), at the end of the phase of the electrical stimulation (middle traces) and after two weeks of the repetitive training (lower traces).

training phase: $p < 0.01$ for the grip strength; stimulation vs training phase: $p < 0.01$ for the peak force of isometric hand extension; stimulation vs training phase: $p < 0.02$ for the peak acceleration during isotonic hand extension).

DISCUSSION

The multiple baseline study design as a single-case design is particularly suited to investigation of the effects of therapeutic interventions irrespective of variations in lesion site, time from onset of stroke, degrees of motor impairment, cognitive status, age and former professional activities (20). In single-case designs, subjects act as their own controls. Spontaneous recovery that is usually most prominent during the early phase following the cerebral lesion (19) is not likely to be responsible for the observed improvements, since they start at the moment when the repetitive training is introduced. This effect, therefore, has to be attributed to the intervention rather than to spontaneous recovery, psychosocial or other environmental factors (5).

Although recent physiotherapeutic approaches (1, 27) emphasize the importance of sensory perception for the restitution of motor deficits, prospective studies concerning the functional value of these approaches are still missing. Until today, techniques aiming at improving sensory function in stroke patients often consist of simple cutaneous and/or proprioceptive stimulations that do not require focused attention or discriminative effort. The present study demonstrates that simple suprathreshold sensory stimulation is of limited functional value. With the exception of spasticity in hand and finger flexors, repetitive electrical muscle stimulation, indeed, does not improve biomechanical nor functional motor parameters of the centrally paretic hand and arm.

The fact that electrical stimulation leads to a spasticity reduction can be explained by the involved

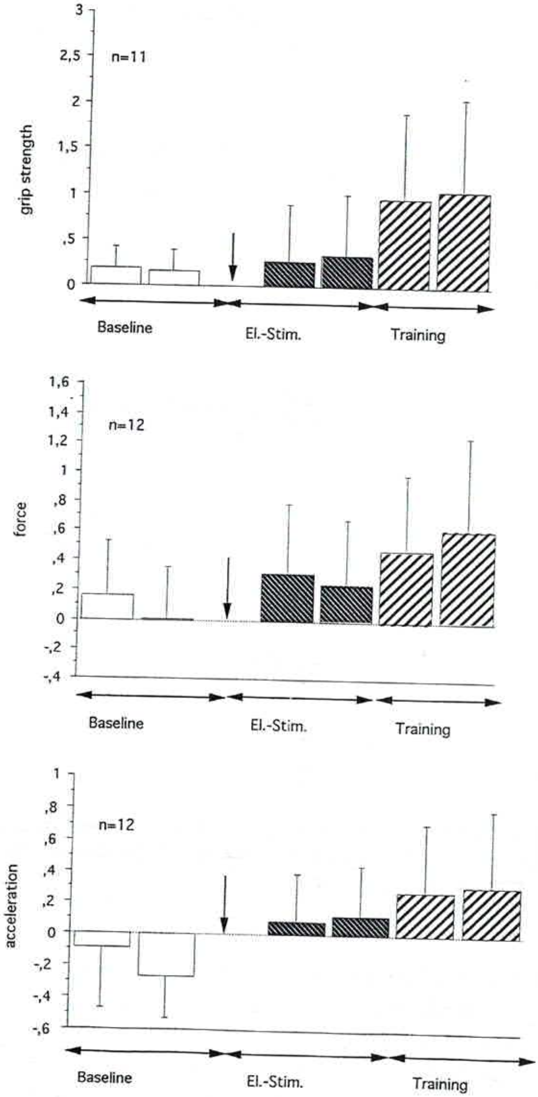

Fig. 4. Development of grip strength, peak force and isometric hand extension and peak acceleration of isotonic hand extension during the baseline, the stimulation and the training phases. The parameters are shown as means and SDs (vertical lines) of the patients' ($n = 12$) performance relative to their last baseline values that were arbitrarily set at zero.

receptors and spinal circuitry. Electrical stimulation as it was used in the present study not only excites the skeletomotor nerve fibres and the muscular tissue, but also proprioceptive, particularly Ia-fibres as well as cutaneous afferents. The net excitatory effect induced in the Ia-fibres by the electrical stimulation probably exceeds the effect of spindle release caused by the muscle contraction (2). Electrical activation of Ia-fibres in the extensor carpi radialis muscle is thought to induce reciprocal Ia-inhibition in the (spastic) hand and finger flexors (14, 32). Furthermore, it is known that cutaneous stimulation of the hand exerts an inhibitory influence on the musculature underlying the stimulated skin (15, 26). The results of the present study correspond to the observations by Lagassé & Roy (22) and Smith (29) that spasticity of the biceps and triceps muscle as well as the degree of co-contraction decrease during functional electrical stimulation (FES) in stroke patients following spontaneous recovery.

Unfortunately, most studies dealing with the influence of simple sensory stimulation procedures on motor function reveal several methodological drawbacks: Baker et al. (6) described the beneficial influence of electrical muscle stimulation on the passive range of motion at the wrist and finger joints, on wrist extension strength and on spasticity in stroke patients. Unfortunately, the evaluation methods are not standardized (except for the measurement of isometric wrist extension strength), a control group is lacking, no functional assessments are presented and other parallel therapeutic interventions cannot be excluded. In an elegant technical approach, Dimitrijevic (11) and Dimitrijevic & Soroker (12) investigated the effect of whole-hand electrical stimulation via a mesh glove in 40 patients with upper motor neuron dysfunction. Reduction of muscle tone and facilitation of isolated hand movements were observed. Unfortunately, the therapeutic interventions have not been limited to the electrical stimulation but are followed by passive stretch of fingers and wrist into neutral position or by volitional finger movements. In some patients whole-hand electrical stimulation above the motor threshold was synchronized with volitional finger flexions and extensions. Furthermore, no control group was presented, and the employed assessments were not standardized.

Unlike the studies by Kraft et al. (21) and by Hummelsheim et al. (16), which were carried out in stroke patients without major sensory deficits, Carey et al. (9) and Yekutiel & Guttmann (35) demonstrated that severe somatosensory deficits of the hand could be alleviated even years after stroke by a retraining programme consisting of cutaneous and proprioceptive discrimination tasks, partly within passive movements. The sensory training, however, was not designed to improve motor function nor was motor function measured in either study (9, 35). Unfortunately, there is a paucity of methodologically sound investigations concerning the influence of complex and discriminative sensory training procedures on voluntary motor capacity.

In comparison to the electrical stimulation, the repetitive training of sterotyped hand and finger movements proved to be an efficient therapeutic intervention since it induced a decrease in spasticity in hand and finger flexors, a significant recovery in overall motor function of the affected arm and an improvement in basic movement parameters of the hand. In particular, the measurement of grip strength amplitude is known to be a useful indicator of the degree of functional motor capacity of the arm (30). The observations during phase C of the present study confirm the results of two previous studies concerning the benefit of repetitive motor training (8, 16).

As could be demonstrated in the present (phase C) and in previous studies, the repetitive element (8) together with a physiologically activated time-locked feedback information from cutaneous and proprioceptive receptors (16, 21) appear to be crucial for motor recovery in hemiparetic patients. Current theories of perceptual learning and recovery of function in people with brain damage, indeed, recommend that meaningful and graded stimuli, active participation (i.e. sensorimotor coupling), and accurate feedback should be used (9, 13, 28).

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Address for offprints:
Horst Hummelsheim
Klinik BERLIN
Department of Neurological Rehabilitation
Free University of Berlin
Kladower Damm 223
DE-14089 Berlin, FRG