

## Original Article

# Transcutaneous functional electrical stimulation for grasping in subjects with cervical spinal cord injury

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**Study design:** Case series.

**Objectives:** To evaluate the benefit, shortcomings and acceptance of a new transcutaneous functional electrical stimulation (FES) technology aimed at improving the grasp function in tetraplegic subjects in acute and postacute rehabilitation.

**Setting:** Spinal cord injury (SCI) centre, university hospital.

**Methods:** Subjects ( $N=11$ ) with complete or incomplete SCI at C4/5–C7 who started FES 1–67 months after their accident were included. Hand function tests, analysis of video recordings and of written documentation of FES sessions, status of muscle strength, and follow-up query were used as outcome measures.

**Results:** Nine subjects used FES as a neuroprosthesis. Eight demonstrated improved grasp function and performance in activities of daily living. In one subject, no benefit from FES was observed. Two other subjects showed improvements in muscle strength and facilitation of active movement with FES. Four subjects successfully integrated FES as neuroprosthesis in everyday life within the rehabilitation centre. Three received the system for home use. The most relevant reasons for stopping the FES application were: (i) improvement of voluntary grasp function, (ii) physical and psychological problems, (iii) no available stimulator for home use, and (iv) insufficient assistance for electrode placement at home. Shortcomings related to the transcutaneous surface technology (eg pain or coactivation of neighbouring muscles) could usually be reduced, or did not limit the efficiency or acceptance of FES. Individually designed digital or analogue control devices were preferred.

**Conclusion:** Tetraplegic subjects in acute and postacute rehabilitation can profit from a new transcutaneous FES system with respect to functional use and independence. It can be implemented in the rehabilitation programme for muscle strengthening and facilitation of voluntary activity. For a successful application of FES, there is a need for individual electrode placement, stimulation programmes, and FES control devices.

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**Keywords:** functional electrical stimulation; spinal cord injury; tetraplegic subjects; grasp function, transcutaneous stimulation

## Introduction

A spinal cord injury (SCI) at a level above T1 often results in a partial or complete loss of the hand function. In these cases, compensatory techniques, adaptations, auxiliary devices, and special training can be used to improve grasp capabilities. One important rehabilitative approach is to enhance the effect of the active tenodesis grasp function (active wrist extension that results in passive finger flexion). In training sessions, patients with

SCI are taught compensatory movements and techniques that help them to interact with objects.

Despite these techniques, the grasp function usually remains considerably restricted, and a further improvement is required. In the last four decades, great effort has been invested at enhancing the quality of functional electrical stimulation (FES) for the improvement of hand function.<sup>1</sup> FES activates paralysed muscles by electrically stimulating peripheral nerves originating from intact lower motoneurons. Different FES systems for improving grasp function have been developed and evaluated, including transcutaneous systems (eg Bionic

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Glove,<sup>2,3</sup> NESS Handmaster,<sup>4,5</sup> Belgrade Grasping System,<sup>6,7</sup> ActiGrip<sup>®</sup> System<sup>8</sup>) and implantable systems (eg Freehand system<sup>9,10</sup>). The Bionic Glove is a noninvasive FES system that uses self-adhesive surface electrodes. One major advantage of the system is the easy donning and doffing of the glove. However, it is limited to clients with C6–C7 SCI because the stimulation is controlled by means of an integrated wrist position sensor that requires active extension of the wrist. The NESS Handmaster consists of a rigid splint with integrated surface electrodes. The construction restricts free electrode placement, inhibits active tenodesis grasp function, and decreases the range of supination; however, the system can be donned and doffed easily and quickly. The Belgrade Grasping System and its successor, the ActiGrip<sup>®</sup> System, allow flexible variation of the stimulation parameters and of predefined grasp patterns, with electrode positioning not restricted to predefined areas. The ActiGrip<sup>®</sup> System has been commercially available since November 2003. These different FES systems are described in a separate review.<sup>11</sup>

Many patients in the Balgrist hospital in Zürich are in the early stages of post-trauma recovery, and consequently require individualistic rehabilitation programmes directed towards particular goals, for example, patients with incomplete SCI need therapies focused on neuronal facilitation and muscle training, those with complete tetraplegia require support of grasp function, and those with paraplegia ask for support of walking function. In such cases of early rehabilitation, surface stimulation technology is preferred to implanted systems, as it can be easily modified and ceased without tissue damage, especially in cases of partial neurological recovery.

In order to cope with differing client requirements, our group in Zurich developed a new transcutaneous FES system.<sup>11–15</sup> Specifically, it is aimed at complying with the following demands: (1) flexibility in the variation of stimulation parameters; (2) easy and fast creation of individual stimulation programmes for muscle training and functional application; (3) applicability in subjects with different injury levels; (4) flexibility in electrode positioning; (5) appropriate control from digital and analogue control sensors. Two different prototypes have been developed and applied, the first was a stationary system,<sup>12,13</sup> and the second a portable system called ETHZ-ParaCare FES system.<sup>11</sup> The disadvantage of the stationary system was the restriction to muscle training and functional training in the rehabilitation centre because it could not be provided to the subjects for home use. The 'Compex Motion' device was subsequently developed, which complied with all of the demands mentioned above.<sup>14,15</sup>

The majority of studies on FES supported hand function include only subjects that are at least 1 year postinjury, and no reports could be found focusing on the effects of FES applied at earlier stages of recovery. Therefore, the aim of this study was to provide a retrospective description of our experiences with FES-

aided grasping in nine acutely injured SCI subjects during their first rehabilitation programme and in two subjects after their first rehabilitation. We report the benefits from the applied systems for the improvement of grasp function and the preconditions required to use the system successfully, while identifying some of the problems that reduce the acceptance of the technology.

## Methods

### *Participating subjects*

A total of 11 SCI subjects (nine male, two female), aged from 15 to 70 years old, participated in the FES programme (Table 1). FES was applied for the first time between 1 and 67 months after injury. Inclusion criteria for the participation were: (1) no active palmar and lateral grasp function (except tenodesis grasp function); (2) no major peripheral nerve lesion; (3) subjects with sufficient proximal arm function, or with expected proximal arm function following mobilisation. None of the subjects underwent surgical operations such as tendon transfers or arthrodesis of the interphalangeal joint of the thumb to enhance hand function. An informed consent to participate in the FES programme was obtained from all subjects, and the programme was approved by the local Ethics Committee.

### *Stimulation devices and parameters*

FES was carried out with a stationary stimulation system<sup>12,13</sup> and two portable systems, the ETHZ-ParaCare FES system,<sup>11</sup> and Compex Motion.<sup>14,15</sup> All stimulation devices were microcontroller-based systems with four current-regulated stimulation channels. The stimulation current amplitudes were individually set for each muscle group to achieve sufficient functional contraction force without pain or uncomfortable sensation.

Low frequency (25 Hz) stimulation was preferred in order to minimise muscle fatigue. However some subjects felt discomfort, and required higher levels (up to 40 Hz) that were subsequently reduced. Controlled muscle contraction was achieved by varying the pulse width between 0 and 250  $\mu$ s.

Generally, a push button (digital) switch was used as the control sensor, because this could be easily installed and fixed on the wheelchair. However, two subjects used EMG signals, and another preferred a sliding potentiometer (analogue control). The reasons for controls other than the push button are presented in the results.

For the transcutaneous stimulation of the extrinsic hand muscles, 50 mm  $\times$  50 mm Compex self-adhesive electrodes were used (Compex SA, Chemin du Devent, 1024 Ecublens, Switzerland). If necessary, the electrodes were resized in order to prevent coactivation of neighbouring muscles. Self-adhesive 15 mm  $\times$  20 mm Medicotest Neuroline Disposable Neurology Electrodes were used to stimulate the thenar muscle (Medicotest A/S, Rugmarken 10, 3650 Olstykke, Denmark).

**Table 1** Data of the participating subjects

Subject	Age <sup>a</sup> (years)	Sex	Start <sup>b</sup>	System	Time between injury and ASIA	ASIA: neurological level (motor)		ASIA: neurological level (sensory)		ASIA: Impairment Scale	Follow-up query after discharge (months)
						Right	Left	Right	Left		
						1	63	M	3		
2	32	M	1	P1, P2	1	C5	C5	C6	C6	A	9
3	15	M	5	St, P1	1	C7	C7	C6	T4	B	23
4	70	F	2	P1	1	C5	C5	C6	C6	C	20
5	17	M	3	St, P1	1	C5	C5	C4	C5	B	—
6 <sup>c</sup>	33	F	67	P1	62	C6	C6	C6	C6	C	34
7	32	M	2	P1, P2	1	C5	C5	C5	C5	A	20
8	25	M	18	P1, P2	18	C5	C5	C4	C4	A	5
9	19	M	7	St	1	C6	C6	C6	C6	A	26
10	33	M	8	St	1	C5	C4	C5	C4	A	50
11	61	M	1	P2	1	C5	C4	C4	C4	C	—

<sup>a</sup>Age (years) at SCI injury<sup>b</sup>Start of FES after injury (months)<sup>c</sup>OutpatientP1: ETHZ-ParaCare FES system;<sup>11</sup> P2: Compex Motion;<sup>14,15</sup> St: Stationary stimulation system<sup>12,13</sup>ASIA = American Spinal Injury Association.<sup>17</sup> A = Complete, B–D = incomplete (details are described elsewhere)<sup>17</sup>

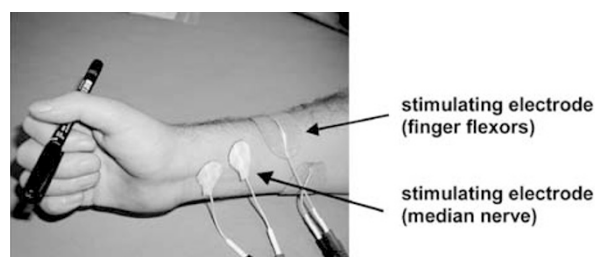
### Stimulated muscles, grasp functions and stimulation patterns

In all subjects, extrinsic finger extensors (m. extensor digitorum), extrinsic finger flexors (m. flexor digitorum superficialis and/or flexor digitorum profundus), and the thumb flexor (m. flexor pollicis brevis) were stimulated to achieve lateral and palmar grasp functions. The only exception was subject 2, whose finger extensors could not be stimulated due to additional lower motoneuron lesions. If it was not painful for the subject, the thumb flexor was stimulated via the median nerve with electrode positions as shown in Figure 1, else electrodes were placed on the thenar muscles. Figure 2 shows typical stimulation patterns used by the subjects, in order to achieve lateral as well as palmar grasp.

### Training procedure and functional application

Identification of the appropriate electrode positions and stimulation parameters was determined in the first FES session. Subsequently, subjects entered the FES training and application programme that comprised four different steps:

1. Muscle strengthening with electrical stimulation. This training phase lasted 3–4 weeks, and comprised of stimulation for 20 min/day between 4 and 7 days/week. The time of stimulation as well as stimulation parameters (amplitude, pulse width, frequency, etc.) were kept unchanged. Only in case of discomfort were parameters adapted.
2. FES-assisted exercises in occupational therapy. Occupational therapists selected functional games or tasks of daily living such as using the telephone,



**Figure 1** Electrode placement for the electrical stimulation of finger flexors and the median nerve for thumb flexion

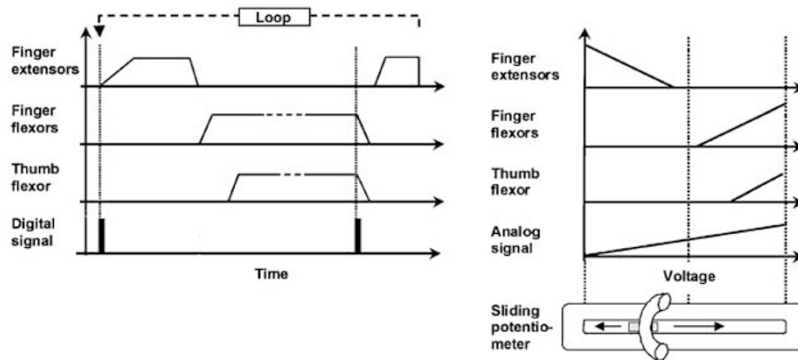
pouring, drinking, handling a videotape, writing, etc. The functional exercises with FES replaced the normal functional hand training conducted in occupational therapy.

3. Application of FES for activities of daily living (ADL) in the rehabilitation centre (eg shaving, brushing teeth).
4. Application of FES for ADL at home.

Assistants who were familiar with the technique and individual electrode placement could don and doff the electrodes and stimulators in about 5–10 min.

### Assessment

**Application logs** The investigators documented in FES application logs (diary) the frequency of FES application, stimulation parameters, types of applied control sensors, problems arising with FES (eg discomforts and factors reducing the efficiency of FES), solutions, and reasons for stopping the application of FES.



**Figure 2** Stimulation patterns. Left: Example of a stimulation pattern with a digital control scheme (push button or EMG signals): The first trigger starts the stimulation of finger extensors. After a defined period (eg 2 s), finger extensors relax, and the stimulation of finger flexors and thumb flexor starts. Hand closure remains until a second digital trigger is achieved. After this second trigger, the flexor muscles relax and the finger extensors are stimulated for a short time. Right: Analogue control (eg sliding potentiometer). The middle part of the slider is neutral, that is, neither finger extensors nor finger flexors are stimulated. The stimulation intensity of finger extensors increases with shifting the handle to the left, and the stimulation intensity of finger flexors increases with shifting the handle to the right. Note that in the digital as well as in analogue control scheme the stimulation of the thumb muscles is delayed with respect to that of the finger flexors in order to ensure that the fingers do not grasp the thumb

As this study is retrospective, assessment of hand function was not the same for all subjects, but contained comparable information. A brief overview is given in the following section, with more detailed information presented in the parts where the case studies are described.

**Videos** Functional tasks like drinking from a cup, or pouring liquid with and without FES were recorded on video. The videos were evaluated by examining how subjects managed to grasp and hold objects with and without FES and whether they could grasp more objects with FES. In both cases, the quality of the grasp was assessed, and information provided about which could be better handled without FES.

**Hand function tests** These tests were used to compare the hand function with and without FES.

1. *Sollerman test*,<sup>16</sup> of which the following subtests were selected: Put a key into a Yale-lock, and turn 90°. Pick up coins from a plain surface and put them into purses mounted on the wall of the test box. Open and close zippers. Pick up the coins from the purses. Lift wooden blocks (size 76 and 102 mm) over a 50-mm high obstacle. Lift iron (weight 6 lbs ie 2.7 kg) over the same obstacle. Turn a screw with a screwdriver (handle 25 mm in diameter). Pick up nuts from a felt-covered surface and put them onto bolts. Unscrew the lid of jars (sizes of 75 and 100 mm) with jars mounted on the wall of the box. Do up buttons. Cut Play-Dough with a knife and fork (commercial design).

A five-graded scale was used according to the guidelines of the test: 0 = the task cannot be performed at all, scores 1–3 = successful performance with gradations considering the time, ease of performance, and use of

the prescribed grip, and 4 = the task is completed without any difficulty within 20 s and with the prescribed hand-grip of normal quality.

2. *Self-designed functional test developed by investigators, including the following tasks:* Grasp – hold (10 s) – release a wooden block (100 and 300 g) and a book. Pour liquid from a Tetra Pak<sup>®</sup> (0.5 l). Enter a floppy disk in the computer and retrieve it. Drink from a mug (empty). Grasp – hold – use – and release a telephone receiver, a spoon, and a ballpoint-pen. Documentation included whether the subject could perform the task or not, and whether the object could only be manipulated bimanually instead of unilaterally.

**Follow-up query** A follow-up query was used to identify the applicability of integrating FES into daily living in the hospital and at home, as well as the reasons for nonuse or eventual cessation of FES. The subjects were asked to mark the applicable answers proposed in a questionnaire and/or to add individual answers. The questions are presented in the Appendix. Question No. 2 included a graded Likert scale from 1 to 7 with 1 = 'not correct' and 7 = 'correct'.

**Assessment of muscle strength** Arm muscle strength was tested to examine its influence on the applicability of FES for grasp function. Physical therapists examined muscle strength using a six-graded scale from 0 to 5 (0 = no voluntary muscle contraction; 1 = visible or palpable contraction; 2 = full range movement without gravity; 3 = full range against gravity; 4 = movement against moderate resistance; 5 = normal force). This scale is also used in the American Spinal Injury Association (ASIA) standards for the assessment of motor deficits in SCI patients.<sup>17</sup> Only muscle tests

performed at least 6 months after injury were evaluated in order to have consistent values.

## Results

### Application of FES

All subjects completed a training programme (Table 2) after which a further eight used FES for functional exercises in therapy (Figure 3). Four subjects applied FES for ADL in the rehabilitation centre, and two used it for ADL at home (subject 6 for 2 years, and subject 7 for several weeks; in subject 5 use remained unclear because contact was lost).

In the following sections, the individual outcomes of the subjects are presented.

### Subject 1

*Objectives of FES:* Muscle strengthening or functional application (when FES was first applied, active hand function was poor with unclear prognosis).

*Functional training with FES:* No functional training was conducted, but muscle training (see below, 'reasons for stopping FES').

*Control sensor:* No control sensor was used (fixed programme for muscle training).

*Assessment:* Sollerman subtest, FES application log (diary), follow-up query.

*Voluntary grasping function:* In the beginning, the subject had weak tenodesis capability and weak grasping capabilities with the thumb and fingers on the stimulated side. On the contralateral side, the subject had active grasp function (score of the Sollerman

subtest was 20/44). Finally, the subject achieved a satisfactory voluntary grasp function on the stimulated side. The score of the Sollerman subtest (performed without FES; test was conducted 4 months after accident resp. 3 months after beginning of FES) was 27/44.

*Results of the follow-up query:* The subject used FES only in therapy because of his physical inability to use it for tasks like brushing teeth, eating, or other activities. After discharge from hospital, the subject did not apply FES any more because there was no significant enhancement of movement by FES.

### Subject 2

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Push button, controlled with the contralateral fist.

*Assessment:* Video recordings of the subject handling different objects with and without FES (video recordings were performed 1, 4 and 5 months after beginning of FES); self-designed functional test; FES application log (diary); follow-up query (not returned).

*Voluntary grasping functions:* The subject had a weak tenodesis grasp on both sides (wrist extension on the left hand: 7.1 Nm, right hand: 4.9 Nm). He could grasp, hold, and release objects like a ball pen, telephone receiver or a Tetra Pak ( $\frac{1}{2}$  l), but the subject had to use both hands.

*Hand function with versus without FES:* The subject was able to grasp more objects, for example, grasp a slippery pocket book. More objects could be handled unilaterally instead of bimanually, for example, handle a glass or

**Table 2** Main applications of FES

Subject	1	2	3	4	5	6	7	8	9	10	11
Training programme	+	+	+	+	+	+	+	+	+	+	+
Functional exercises in the therapy		+	+	+	+	+	+	+	+	+	
ADL in the rehabilitation centre		+		+	+		+				
ADL at home					?	+	+				



**Figure 3** Sequence of grasping with FES. Subject with tetraplegia (C5 complete), grasping a fork by functional stimulation of paralysed forearm muscles. Opening of the hand is achieved by stimulation of forearm extensor muscles (left picture). For grasping, finger flexor muscles in combination with distal median nerve are stimulated (middle and right pictures)

cup. There was more flexibility regarding the grasping site and forearm position, for example, carry a  $\frac{1}{2}$  l bottle, videotape, a small sandbag that changed its form when grasping, and a mouse pad vertically instead of balancing the object in the supinated hand. A tube of toothpaste could be held at its end. A hole punch could be carried safely with palmar grasp instead of hooking fingers into, and supporting in the supinated hand. Grasp was safer, for example, a plastic bottle (diameter 45 mm, weight 160 g) could be hit against the table without slipping in the hand. Nails could be driven into a wooden board with FES using a normal hammer (grip covered with antislip foil). Without FES, hammering was not possible because the grip slipped. More ADL could be performed in the therapeutical setting, for example, drink from a cup.

*Use of FES for ADL in the rehabilitation centre:* The subject achieved a higher level of independence in ADL in the rehabilitation centre, for example, eating, drinking, brushing teeth, shaving and smoking.

*Limiting factors of FES application (documented in the FES application log):* Insufficient trunk stability moderately impaired the control of FES, as the subject used the contralateral arm for stabilisation. On both sides, it was not possible to generate finger or thumb extension by FES. Passive hand opening decreased during rehabilitation on the stimulated side. This hindered the subject's ability to place his hand around larger objects. Unwelcome coactivation was observed in wrist flexors when stimulating finger flexors. For this reason, a wrist brace was used to stabilise the wrist.

*Reasons for stopping FES:* Because of drug abuse, clinical staff set other therapeutic priorities.

#### Subject 3

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Push button, controlled with the contralateral fist.

*Assessment:* Sollerman subtest, performed without FES (test was conducted 3 months after accident, that is, before FES was started); follow-up query.

*Voluntary grasping and arm functions:* The subject had a strong tenodesis grasp. The score of the Sollerman subtest was 17/44.

*Limiting factors of FES application:* The subject tried FES for functional use only a few times because of pain.

*Answers of the follow-up query:* The subject used FES in therapy sessions, but not for ADL outside the therapy sessions. This was because: the subject did not feel like it, there was always a hurry so that nurses had to help, the FES system did not work properly, the subject never

had in mind to use FES outside the therapy sessions, and all activities, for which FES could have been applied, could be accomplished without FES (all arguments scored with 7 on the scale). After discharge from hospital the subject no longer applied FES. The main reason for stopping FES was that its application was too time-consuming (argument not specified). If the subject would use FES at home, requirement of assistance for donning and doffing a glove would be no problem, because assistance anyway in the morning and evening was needed.

#### Subject 4

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Push button, controlled with the contralateral fist.

*Assessment:* Video recordings of the subject handling different objects (first video recordings 11 weeks after beginning of FES: tasks performed with and without FES; second video 5 months after beginning: tasks performed without FES); FES application log (diary); follow-up query (returned from relatives without answers because the subject deceased in the meantime).

*Voluntary grasping and arm functions:* In the beginning of FES the subject had a weak tenodesis grasp and no active finger functions. After 4 weeks, the subject had limited voluntarily flexion of the thumb and index finger on the stimulated side. At 5 months after beginning of FES the subject had a weak active grasp and was very skilled. For instance, the subject was able to plug a connector in and out of a socket, pour liquid out of a 1 l Tetra Pak, take a pin out of a foam and put it in again, drink from a glass, punch holes in sheets of paper, and stitch together sheets of papers.

*Hand function with versus without FES (11 weeks after beginning of FES):* The subject could handle more objects unilaterally instead of bimanually, for example, hold a filled glass or cup with one hand. More ADL could be performed in the therapeutical setting, for example, drink from a cup.

*Use of FES for ADL in the rehabilitation centre:* The subject used FES in ADL after 6 weeks of training. The subject's level of independence was improved by using FES. It was mainly applied for eating, drinking, and brushing teeth.

*Limiting factors of FES application:* In the beginning of the muscle strengthening period, FES was painful. Pain could be reduced by placing the electrodes directly on the thenar muscle belly instead of stimulating thumb muscles via the median nerve at the distal forearm. Unwelcome coactivation was observed: wrist flexors were coactivated with finger flexors. For this reason, a wrist brace was used to stabilise the wrist.

*Reasons for stopping FES:* Severe depression seven weeks after beginning of FES resulted in a reduced compliance, and 11 weeks after start FES was interrupted. The subject achieved a satisfactory grasp function without FES by voluntary finger movements.

*Further observations:* More finger and thumb muscles (flexors and extensors) regained voluntary activity and the function improved more on the stimulated side than on the nonstimulated side. In this subject the finger flexors developed severe flexor spasticity only on the nonstimulated side.

*Subject 5*

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Sliding potentiometer, controlled with the contralateral fist. The subject favoured this control sensor because of taking the FES system to his Arabian home country, and the subject assumed that this sensor was less suspect.

*Assessment:* Video recordings of the subject handling different objects with and without FES (videos at 4 and 7 months after beginning of FES); FES application log (diary); follow-up query was not possible because contact to the subject was lost.

*Voluntary grasping and arm functions:* The subject had neither voluntary finger activity nor tenodesis grasp. Both arms could voluntarily be lifted and moved.

*Hand function with versus without FES:* More objects could be grasped, for example, lift a 250 ml Tetra Pak. More objects could be handled unilaterally instead of bimanually, for example, handle a telephone receiver. There was a higher flexibility regarding the grasping site and forearm position, for example, an apple could be held in pronation instead of balancing it in the supinated hand. Grasp was safer, for example, the subject could shake a telephone receiver in one hand without slipping. More ADL could be performed, for example, pour liquid from a 250 ml Tetra Pak, make a phone call.

*Use of FES for ADL in the rehabilitation centre:* The subject used FES functionally for ADL in the rehabilitation centre for eating, drinking, brushing teeth, and writing. These tasks could not be performed without FES.

*Limiting factors of FES application:* Insufficient trunk stability moderately impaired control of FES as the subject used the contralateral arm for stabilisation.

*Use at home:* The subject took the system home. It remains unclear whether and how long the system was used because contact was lost.

*Subject 6 (outdoor patient)*

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Push button, controlled with the contralateral fist.

*Assessment:* Sollerman subtest, performed with and without FES (test was conducted 6 weeks after beginning of FES); FES application log (diary); report of the occupational therapist during the outpatient treatment; follow-up query; status of muscle strength at the time of functional use of FES (5½ years after accident; results see Table 3).

*Voluntary grasping and arm functions:* The subject had a weak tenodesis grasp. The score of the Sollerman subtest was 5/44.

*Hand function with versus without FES:* The score of the Sollerman subtest was 5 points higher with FES, that is, 10/44. The subject could perform more ADL in the therapeutical setting, for example, open envelopes, zippers, bags, and tubes, cut with a knife, hold a playing cards holder.

*Results of the follow-up query:* The subject used FES at home for 2 years, for example, for brushing teeth, writing, and holding books. Eventually FES was stopped because of electrode defects, unreliability of the first portable prototype, the complicated and time-consuming donning and doffing of the system, and the weight of the device. If the adjustment of the FES system would take only 5 min, the requirement of

**Table 3** Status of muscle strength

Subject	6	7	8	10	11
	Yes	Yes	Yes	Yes	No
<i>Application of FES for ADL possible</i>					
Deltoides p. clavicularis	3	5	4	3	1
Deltoides p. acromialis	3	5	4	3	3
Deltoides p. spinalis	3	5	4	3	1
Pectoralis major	3	2	1	0	2
External rotator muscles	2	4	4	4	2
Internal rotator muscles	2	3	2	0	4
Triceps brachii	0	0	0	0	1
Biceps brachii	4	4	5	3	4
Pronators	3	1	0	1	1
Supinators	3	4	4	1	4
Extensor carpi radialis	3	3	3	0	0
Extensor carpi ulnaris	0	1	0	0	0
Extensor digitorum	0	0	0	0	0
Flexor digitorum	0	0	0	0	0
Adductor pollicis	1	2	0	0	0
Abductor pollicis	0	0	0	0	0

0 = no voluntary muscle contraction; 1 = visible or palpable contraction; 2 = full range movement without gravity; 3 = full range against gravity; 4 = movement sustaining moderate resistance; 5 = normal force

assistance would be no problem, because assistance was already necessary in the morning and evening.

*Limiting factors of FES application:* The subject had a clawhand with subluxation of the metacarpophalangeal joints that mechanically reduced efficiency of FES.

#### Subject 7

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Push button, controlled with the contralateral fist.

*Assessment:* Video recordings of the subject handling different objects with and without FES (video recordings were made 6 months after beginning of FES; additionally, the subject participated 2 years later in a professional video for the company involved in the development of the FES device); FES application log (diary) and personal communication after discharge regarding home use; follow-up query (not returned); status of muscle strength (3 years after accident: see Table 3; in addition, status for the evaluation of tenodesis grasp was obtained at the beginning of FES and at discharge).

*Voluntary grasping and arm functions:* In the beginning of FES, the subject had no tenodesis grasp (score: 0 in the status of muscle strength). At 6 months after accident the wrist could voluntarily be extended without gravity (score: 2), and when measured after 3 years, it could be extended against gravity (score: 3). With this weak tenodesis grasp, the subject was able to hold and handle light objects such as an empty PET-bottle or a floppy disk. For heavier objects both hands were used, for example, drinking from a tin (0.33 l).

*Hand function with versus without FES (at the time when he had already weak tenodesis grasp):* The subject was able to grasp more objects, for example, grasp a can with a handle filled with 500 ml coffee. More objects could be handled unilaterally instead of bimanually, for example, grasp a 0.33 l Cola can. More flexibility could be observed regarding the grasping site and forearm position, for example, carry a videotape, a floppy disc, and an adapted key (its head was enlarged with a flat plastic disk) vertically. Grasp was safer, for example, the subject could shake mean-weight objects like a videotape or telephone receiver without slipping. More ADL could be performed in the therapeutical setting, for example, pour coffee from can filled with 500 ml coffee.

*Use of FES for ADL in the rehabilitation centre:* The subject used FES functionally for ADL in the rehabilitation centre for eating, drinking, brushing teeth, and shaving.

*Special observations:* The subject regained voluntary tenodesis grasp and thumb adduction only on the stimulated side.

FES enhanced compliance in occupational therapy. Before FES was started, the subject refused to exercise hand function because of pessimism in this regard. FES enabled the subject to grasp objects and to perform ADL, and due to this positive feedback the subject also started to exercise hand function without FES.

*Limiting factors of FES application:* Insufficient trunk stability moderately impaired control of FES as the contralateral arm was used for stabilisation.

If the subject was prepared to grasp an object, that is, approached and touched the object, contact could be lost when the stimulation of finger extensors started. With tenodesis grasp pegs and wooden blocks could be manipulated faster without FES than with FES.

*Use at home:* The subject took the system home, but used it only sporadically within the first weeks after discharge.

*Reasons for stopping FES:* The subject had difficulties to find assistance at home for placing and fixing the electrodes.

#### Subject 8

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* Push button, controlled with the contralateral fist.

*Assessment:* Video recordings of the subject of handling different objects with and without FES (video recordings were made 7 weeks after beginning of FES); FES application log (diary); follow-up query (not returned); status of muscle strength 1½ years after accident, that is, at the beginning of FES (results: see Table 3).

*Voluntary grasping and arm functions:* The subject had a weak tenodesis grasp, that is, the score of wrist extensors was 2 according to the muscle strength score. The subject could lift a weight of up to 200 g attached to stiff paper, insert and remove a floppy disk, insert a key (its head was enlarged with a flat plastic disk), and lock.

*Results of the observations from video tapes (with FES versus without FES):* The subject could grasp more objects, for example, lifting weights up to 500 g attached to stiff paper. More objects could be handled unilaterally instead of bimanually, for example, handle the adapted key unilaterally and remove a floppy disk from the drive. Higher flexibility was observed regarding the grasping site and forearm position, for example, a videotape or a floppy disk could be carried vertically. Grasp was safer, for example, the key dropped several times without FES, but could be handled safely with



FES. More ADL could be performed in the therapeutic setting, for example, remove the key from the lock and remove a power plug from an outlet.

*Use of FES for ADL in the rehabilitation centre:* The subject tried to use FES functionally for catheterisation, but failed.

*Limiting factors of FES application:* The subject felt pain in the beginning of the muscle strengthening period. Pain could be reduced by starting at a lower intensity and progressively increasing the current in order to habituate the subject to the stimulation. Sometimes the subject lost contact with the object as soon as the finger flexors were stimulated for lateral grasp. Some light and small objects such as wooden gaming pieces could be handled faster without FES.

*Use at home, reasons for stopping FES:* The subject wanted to take the system home, but no portable stimulator was available for home use.

#### *Subject 9*

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* First, a sliding potentiometer was tried that reduced the option to work bimanually. As a consequence, the subject performed tasks slower with FES than without. Analogue and digital EMG control strategies were tried using the muscle activity from the contralateral m. pectoralis or m. trapezius and the ipsilateral m. extensor carpi radialis. The subject clearly preferred the latter option.

*Assessment:* Video recordings of the subject handling different objects with and without FES (video recordings were taken 7 weeks after beginning of FES; FES application log (diary); follow-up query (not returned); status of muscle strength 1 month after his accident for the evaluation of his tenodesis grasp.

*Voluntary grasping and arm functions:* The subject had a strong tenodesis grasp, that is, already 1 month after his accident the score of the m. extensor carpi radialis was 4 according to the muscle strength score. The subject could insert and remove a floppy disk, handling the telephone receiver/making a telephone call, holding books or journals, combing, shaving, etc.

*Results of the observations from video tapes (with FES and without FES):* The subject was able to grasp *more objects*, for example, carry a 1 l bottle. Grasp was safer, for example, shake objects like a broom without slipping. More ADL could be performed in the therapeutic setting, for example, writing.

*Use of FES for ADL in the rehabilitation centre:* The subject did not use the system for ADL out of therapy sessions.

*Limiting factors of FES application:* Unwelcome coactivation was observed in wrist extensor and supinator muscles when stimulating finger extensors.

Switching the forearm from pronation to supination during stimulation caused inconvenience in two ways. When finger extensors were stimulated, the subject felt pain in the supinated position. Pain could be reduced by reducing the pulse width and increasing the stimulation amplitude instead. When finger flexors were stimulated during the change from pronation to supination, strength of palmar grasp function was reduced about 10–20%. All in all, positive effects of FES were small.

*Use at home, reasons for stopping FES:* The subject wanted to take the system home, but no portable stimulator was available for home use.

#### *Subject 10*

*Objectives of FES:* Use as a neuroprosthesis.

*Control sensor:* The subject had no proximal function on the contralateral side (except modest protraction and retraction of the shoulder) and was not able to serve a push button. Thus, the EMG activity of the contralateral shoulder could be used as a control signal.

*Assessment:* Video recordings of the subject handling different objects with FES (video recordings were made 8 weeks after beginning of FES); FES application log (diary); follow-up query; status of muscle strength at the beginning of FES, that is, 8 months after accident (results: see Table 3).

*Voluntary grasping and arm functions:* The subject had no active ipsilateral tenodesis grasp and no proximal function on the contralateral side. Without FES, the subject was neither able to grasp bimanually nor unilaterally.

*Results of the observations from video tapes (with FES):* FES enabled the subject to grasp, hold and release objects like a cylinder, an electric shaver or a 250 ml Tetra Pak. ADL could be performed in the therapeutic setting, for example, pour liquid from a 250 ml Tetra Pak and make a phone call.

*Answers of the follow-up query:* The subject used FES in therapy sessions, but not for ADL outside therapy sessions, because of the physical inability to use it for tasks like brushing teeth, eating, or other activities. After discharge from hospital the subject did not apply FES anymore. Personal reasons for stopping FES were not mentioned. If the subject would use FES at home, requirement of assistance for donning and doffing a glove would be no problem, because assistance in the morning and evening was needed anyway.

*Use of FES for ADL in the rehabilitation centre:* The subject could not use the system for ADL because he had no portable stimulator.

*Use at home, reasons for stopping FES:* No portable stimulator was available for home use.

#### *Subject 11*

*Objectives of FES:* Muscle strengthening or functional application (when FES was first applied, active hand function was very poor with unclear prognosis).

*Stimulated muscles:* Finger muscles (as described in 'Methods'), m. biceps and m. triceps brachii.

*Control sensor:* Push button (controlled by the therapist) or no control (automatic programme for muscle training).

*Assessment:* FES application log (diary); status of muscle strength 4 months after beginning of FES, that is, 5 months after accident (results: see Table 3).

*Voluntary grasping and arm functions:* The subject had no grasping function, that is, no tenodesis grasp and only a weak proximal function (see Table 3) on the stimulated side. The function of the other arm was better (score 2 in the status of muscle strength for shoulder flexion, extension, and horizontal abduction), but not sufficient to grasp and manipulate objects bimanually.

*Results of the observations with FES:* Grasping function could not be achieved during 7-month treatment because of persistent weakness of proximal arm muscles such that the subject could not reach an object. Also, the grasp force with FES was not strong enough, for example, a bottle (weight 160 g, diameter 45 mm) could not be held safely.

*Development of voluntary function could be observed:* At 3 months after starting FES he developed voluntary activity of stimulated muscles, that is, slight voluntary finger movement was observed. Some weeks later, FES was also applied on the contralateral forearm muscles, which consecutively developed slight voluntary muscle contraction.

*Limiting factors of FES application:* Lower motoneuron damage and transient oedema resulted in reduced motor responses to FES.

*Use at home, reasons for stopping FES:* Insufficient recovery of proximal arm muscles, hypertonia of the biceps muscle, pronounced supine forearm posture, and no progress of voluntary grasping function led to the decision of the FES team not to continue FES after discharge.

#### *Muscular preconditions for successful application of FES for ADL*

In subjects who could use FES functionally, all parts of the deltoid muscle and the biceps had a minimum value of 3 (Table 3). The minimum value of the external shoulder rotator muscles was 2. All other muscles of the upper extremity had a minimum value of 0 or 1. In the subject who could not use FES functionally, the anterior and posterior parts of the deltoid muscle were below the minimum value of 3.

#### **Discussion**

This report describes our experiences with transcutaneous FES for the hand function and shows benefits from FES and problems.

#### *FES application during early rehabilitation*

The transcutaneous FES technology can be applied during early rehabilitation of SCI subjects for different purposes. Owing to its flexibility, the system can be used for muscle training, to support independence in ADL during early rehabilitation, and to facilitate functional hand movements. The latter has been shown to be due to the activity-dependent neuronal plasticity and by providing additional natural feedback.<sup>18–20</sup>

In patients with a lesion at a C6/7 level the recovery of voluntary function is variable and frequently leading to a functional tenodesis grasp, which improves independence. Not only physical conditions, but also the psychological and social situations determine the success of FES application. The importance of these factors are underlined by other studies: One subject out of six stopped FES because of psychological problems.<sup>21</sup> In adolescent subjects, the ability to use FES regularly at home relied on adequate family support.<sup>22</sup> The long-term use of FES depends upon the subject's physical, psychological and social conditions. During early rehabilitation up to the first months at home, surface FES technology should therefore be preferred compared to an implanted system because it provides flexible opportunity to identify the improvement of hand function and applicability of FES at home without surgical procedures and final solutions.

#### *Improvement of grasp function with FES*

Improvement of grasp function using our FES systems was reflected by the ability to grasp more objects, to carry objects safer, to transfer more objects independent of forearm position, to grasp and carry objects with unilateral instead of bimanual grasp, and to enhance independence in ADL. The most important improvements were observed in those subjects who were not able to grasp bimanually and/or had no tenodesis grasp. In contrast, subjects who had a good tenodesis grasp experienced only small improvements with FES (subject 9) or no substantial differences (subject 3). Other studies using surface or implantable systems confirm these

benefits.<sup>2,3,5,9,10,22–25</sup> Smaller objects such as pegs and wooden blocks could be manipulated better with an active tenodesis grasp rather than with FES because the position of the object within the hand can better be corrected, and there is no time required for the interaction with the device. For heavier and slippery objects FES was advantageous or necessary.

#### *Preconditions for a successful application of FES for ADL*

One of the preconditions for a successful FES supported grasp in ADL is the ability to move the arm in the three-dimensional workspace, that is, proximal arm muscle function has to be sufficient to reach and transfer objects. Muscles that enable elbow flexion and shoulder flexion, abduction, and extension must therefore have a minimum motor score of 3, as demonstrated in our data. In contrast, voluntary elbow extension, supination, and pronation movements are not essential since their action can be partly compensated by adduction, abduction, and humeral rotation. If wrist extensors are paralysed, no active tenodesis grasp function is possible with the consequence that grasp function can only be achieved by FES. In subjects who have an active tenodesis grasp, the benefit of FES is limited. However, a voluntary wrist extension can be advantageous to control an FES stimulator by extensor EMG activity or a wrist angle goniometer. This mode of control was preferred by one of our subjects and is regularly applied by the Bionic Glove.<sup>2</sup>

#### *Possible solutions for observed problems*

Some physical constraints that limit the successful application of FES might be solved by surgical procedures. The hyperextension of the metacarpophalangeal joints of subject 6, for example, might be reduced by a surgical intervention known as the Zancolli lasso operation procedure.<sup>26</sup> This method was applied in combination with an implantable FES system.<sup>9,24</sup>

In subject 2, the reduced passive hand opening was suspected to be due to an imbalance between the electrically stimulated finger flexors and denervated finger extensors, resulting in a finger flexor bias. Regular passive extension of the fingers might counteract such a development. If finger flexors and extensors can be stimulated, FES can prevent flexor muscle hypertonia as was observed in subject 4. A reduction of flexor hypertonia due to FES was also found elsewhere.<sup>3</sup>

The importance of providing different digital or analogue control for FES has been previously reported<sup>27</sup> and clearly apparent in our subjects.

#### *Outlook*

This report reflects our clinical experience with transcutaneous FES supported grasping in tetraplegic subjects over the last 5 years. Technological advances are underway to enhance the quality of stimulation and

control devices. For example, a special garment for easier application of FES for daily use is under development that can be combined with the portable Compex Motion system.<sup>15</sup> Once the electrodes are appropriately adapted and fixed in the garment, this system can be donned and doffed within short time, a factor that seems to be an essential requirement for better acceptance of FES technology.

#### **Conclusion**

Subjects with a cervical SCI can benefit from transcutaneous FES of hand muscles during rehabilitation with respect to muscle strengthening, facilitation of voluntary muscle activity, and improvement of ADL functions. A surface FES system is more useful in early phase of rehabilitation because it is flexible in its application and it does not need surgical procedures. High flexibility with respect to electrode placement, stimulation programmes, and FES control devices is required in order to adapt the system to the individual needs. For daily use, a more convenient garment is required that can be donned and doffed in a short time by health-care providers or relatives.

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## Appendix: Follow-up query

1. For which application did you use FES in the rehabilitation centre?

*(Please tick appropriate answers and comments if necessary)*

- I used FES only in therapy sessions
  - I used FES functionally outside of therapy sessions, too:
    - as an aid for shaving, brush one's teeth, or similar
    - as an aid for eating
    - as an aid for writing
    - as an aid for catheterising
    - for other activities:
- \_\_\_\_\_
- \_\_\_\_\_

2. If you answered the last question with: 'I used FES only in therapy sessions', what were the reasons for not using it outside of therapy?

*(Please tick appropriate answers and add comments if necessary)*

- I was physically not able to apply it for tasks like brushing teeth, eating, or other activities
- I was physically able to use FES for certain activities, but *(Please evaluate all criteria)*:
  - I did not feel like it  
Not correct       correct
  - There was always a hurry so that nurses had to help me  
Not correct       correct
  - Principally I prefer help  
Not correct       correct
  - Nobody could be found to place the electrodes and set up the system  
Not correct       correct
  - The FES system did not work properly  
Not correct       correct
  - I never had in mind to use FES outside of therapy sessions  
Not correct       correct
  - I could accomplish all activities, for which I could have applied FES, without FES  
Not correct       correct

Do you have further reasons that were not mentioned yet?

*(Please specify and evaluate on the scale; otherwise continue with next question)*

● \_\_\_\_\_  
Not correct       correct

● \_\_\_\_\_  
Not correct       correct

3. How long did you apply FES after discharge?

- I did not apply FES since discharge from hospital
- I applied FES after discharge for
  - 1-3 months
  - 3-6 months
  - 6-12 months
  - longer than 1 year
- I still use FES

4. If you do not apply FES any more: What were the five main reasons for stopping FES?

*(Please answer shorthand)*

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

5. Let us assume that FES would be a good help in daily living for you, and you had a glove with electrodes fixed on appropriate spots.

However, you needed assistance for donning the glove in the morning and doffing in the evening, taking 5 min each.

How acceptable would the requirement of assistance be for you?

*(Please tick off only one answer)*

- If assistance for donning and doffing was necessary, I would rather renounce on FES
- Best I would like to manage it myself, but if only short assistance was necessary, I could accept and organise.
- This would be no problem, because I need assistance anyway in the morning and evening.