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Development of a non-invasive, multifunctional grasp neuroprosthesis and its evaluation in an individual with a high spinal cord injury*

Rüdiger Rupp, *Member, IEEE*, Alex Kreilinger, Martin Rohm,
Vera Kaiser and Gernot R. Müller-Putz

Abstract — **Over the last decade the improvement of a missing hand function by application of neuroprostheses in particular the implantable Freehand system has been successfully shown in high spinal cord injured individuals. The clinically proven advantages of the Freehand system is its ease of use, the reproducible generation of two distinct functional grasp patterns and an analog control scheme based on movements of the contralateral shoulder. However, after the Freehand system is not commercially available for more than ten years, alternative grasp neuroprosthesis with a comparable functionality are still missing. Therefore, the aim of this study was to develop a non-invasive neuroprosthesis and to show that a degree of functional restoration can be provided to end users comparable to implanted devices. By introduction of an easy to handle forearm electrode sleeve the reproducible generation of two grasp patterns has been achieved. Generated grasp forces of the palmar grasp are in the range of the implanted system. Though pinch force of the lateral grasp is significantly lower, it can effectively used by a tetraplegic subject to perform functional tasks. The non-invasive grasp neuroprosthesis developed in this work may serve as an easy to apply and inexpensive way to restore a missing hand and finger function at any time after spinal cord injury.**

I. INTRODUCTION

Patients with restrictions of hand and arm function as a consequence of an injury of the cervical spinal cord are most handicapped [1]. Therefore every form of improvement of a missing or weak grasp function will result in a large gain of quality of life. If surgical options in form of tendon transfers [2] are missing due to an insufficient number of strong muscles under voluntary control, Functional Electrical Stimulation (FES) is the only clinically applicable method for improving the grasp function in persons with a spinal cord injury (SCI) [3]. At the current state of the art a demonstrably functional improvement could be achieved in tetraplegic patients with stable, active shoulder and elbow function, but restricted control of hand and fingers. Especially with the use of implantable systems a long-term stable, easy to handle application is possible [4]. The most sophisticated grasp neuroprosthesis up to now used in a large population of end-users is the Freehand system developed in Cleveland in the 1980s [5], which has been commercialized in 1996. This system provided an end user with two different grasp patterns namely a lateral pinch for grasping small items, e.g. a pen or a fork, and a palmar grasp for manipulating larger objects. A Freehand user is able to fully control his grasp by movements of the contralateral shoulder recorded with a two-axis shoulder position sensor. Despite its proven clinical success and high acceptance of its users this system has not been commercially available since 2001 and thus, cannot be applied routinely to individuals with SCI.

The aim of this work is to show, that (i) the multi-functionality of the Freehand system can also be provided to SCI end-users non-invasively and (ii) that reproducible grasp patterns can be achieved in real-world situations with the help of a personalized forearm electrode fixation sleeve.

II. METHODS

A. Description of the study participant

The individual we included in this single case study is a right-handed 21 year old woman with a traumatic spinal cord injury since January 2009. She is affected by a complete motor and sensory lesion (ASIA Impairment Scale A) with a neurological level of injury of C4 and a motor level of C5. The person with SCI performed a stimulation training of the forearm muscles over several weeks, but very irregularly due to limited time resources of herself and her caregivers. The residual volitional muscle activation of her right upper extremity is as follows:

Shoulder: active abduction, extension and flexion up to 90°; all grade 3/5; full rotational range of motion (ROM), full passive ROM.

Elbow: active flexion (M. biceps grade 3/5 and M. brachioradialis grade 2/5); no active extension (triceps grade 0/5); full passive ROM.

Forearm: active supination (grade 4/5) possible; no active pronation (grade 1/5), but passive pronation possible by trick movement; almost full passive ROM.

Wrist, thumb and fingers: no active movements possible (grade 0/5); almost full passive ROM in finger joints; full wrist and thumb ROM.

All arm muscles could be stimulated sufficiently except the M. carpi radialis, which showed severe signs of denervation.

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R. Rupp and M. Rohm are with the Spinal Cord Injury center of Heidelberg university hospital, 69118 Heidelberg, Germany (phone: +49 6221 56 29230; fax: +49 6221 56 29234; e-mail: ruediger.rupp@med.uni-heidelberg.de).

G.R. Müller-Putz, A. Kreilinger and V. Kaiser are with the Institute of Knowledge Discovery, Graz University of Technology Graz, Austria (e-mail: gernot.mueller@tugraz.at).

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B. *Setup of the Functional Electrical Stimulation*

Our aim was to implement the two grasp patterns implemented in the Freehand grasp neuroprosthesis and to find a practical way for their reproducible generation. One major request was to use surface electrodes placed only on the forearm eliminating the need for electrodes on or inside the hand. First, the lateral grasp pattern providing the ability of picking up flat objects between the flexed fingers and the flexing thumb has been achieved by stimulation of the finger (M. ext. digitorum communis, electrode pair (EP) 1 in Fig. 1) and thumb (M. ext. pollicis longus, EP 2 in Fig. 1) extensor muscles for hand opening, the finger flexors (M. flex. digitorum superficialis, M. flex. digitorum profundus) for hand closing, and the thumb flexor (M. flex. pollicis longus) for grasping. In this woman it was possible to stimulate the flexor muscles of the fingers and the thumb with one common electrode pair (EP 3 in Fig. 1). By using a dedicated stimulation profile it has been possible to use a co-contraction of the thumb flexor and extensor muscles to achieve a state, in which the finger are sufficiently flexed and the thumb is still in an extended position. This stimulation profile has been iteratively determined during an initial screening session.

Second, for the palmar grasp a branch of the median nerve innervating the M. opponens has been selectively stimulated with an electrode pair (EP 4 in Fig. 1) placed on the medial side of the forearm. Due to the small diameter of the forearm and the associated space limitations electrode pairs 2 (M. ext. pollicis) and 4 (M. opponens) share one common electrode.

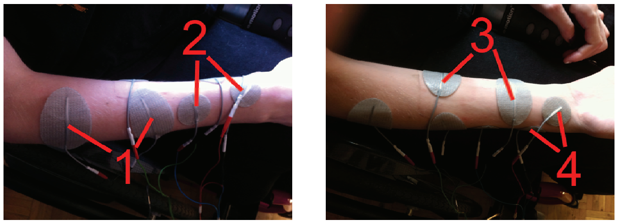

Figure 1. Electrode positions together with the assigned channel numbers of the Motionstim. Due to space limitations channel 2 (M. ext. pollicis) and channel 4 (M. opponens) share one common electrode.

After the appropriate electrode positions have been defined during the initial setup session, a self-adhesive velcro strip is stuck on the top of the electrodes (Fig. 2A). The complete forearm is then covered by a Neopren sleeve. This sleeve is manufactured according to the individual anatomy (proximal and distal diameter, length) of the forearm. The velcro strips hold the electrodes in a fixed position in the sleeve, which dramatically reduces the time for donning (Fig. 2B). The sleeve together with the electrodes has a total weight below 100 g. Therefore, it does not put any relevant additional load to the forearm (Fig. 2C) and doesn't restrict the residual capabilities of the user. The sleeve contains a hole for the thumb and a mark sign at the proximal end, which facilitates the correct positioning of the sleeve on a daily basis. As a precondition for a functional grasp the wrist needs to be stabilized in neutral position during flexion of the fingers. Due to the lack of a voluntary wrist extension (M. extensor carpi radialis muscle, grade 0/5) and a denervation of the wrist extensor muscle in our end user, it was not possible to achieve a stable dorsal extension of the wrist by stimulation. This forced us to integrate a fixation splint made of aluminium into the sleeve.

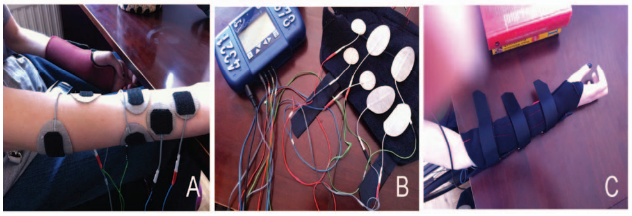

Figure 2. A: Velcro strips stuck on the top of the electrodes, B: electrodes fixed in the Neopren sleeve, C: electrode sleeve mounted on the forearm.

For stimulation an 8-channel surface stimulator (Motionstim 8, Medel, Hamburg, Germany) has been used. A dedicated firmware has been developed for implementation of an individual pulse width map, which can be controlled by the assignment of an analog input signal, e.g. derived from a shoulder position sensor, to the map nodes (Fig. 3). Pulse currents were set individually (EP1: 14mA, EP2: 16mA, EP3 and EP4: 15mA) and held constant during the force measurements and the functional tasks. The pulse frequency was fixed at 20 Hz for a sufficiently powerful tetanic contraction without causing too much fatigue.

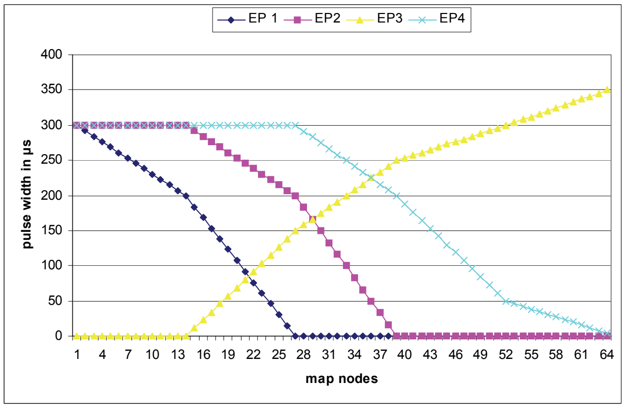

Figure 3. Pusle width map for generation of a lateral and palmar grasp pattern. EP = electrode pairs corresponding to Fig. 1.

C. *Force and functional measurements*

For evaluation of the two different grasp patterns instrumented force measurements using the Pablo device (Tyromotion, Graz, Austria) were performed. Pablo is a dedicated measurement system for the hand, with which the force of the lateral and palmar grasp can be separately assessed (Fig. 4). In case of the lateral grasp the pinch force of the thumb is recorded. Data have been obtained from 10 consecutive measurements of flexion and extension of the palmar grasp and 10 for flexion of the lateral grasp.

For the evaluation of the overall performance of the grasp neuroprosthesis several subtasks of the Grasp-and-Release Test (GRT) [6] without and with FES support were performed. To achieve more representative results a prolonged test time of 120 sec instead of the prescribed 30 sec was used for each of the tasks. The tasks were the following: (i) lifting a cylindrically shaped can on top of a box with 6 cm height; (ii) putting wooden blocks and (iii) pegs inside the box; (iv) lifting a paperweight and (v) a VHS tape on top of the box. The subject was instructed to use the appropriate grasp pattern for each of the tasks, which was the lateral pinch for tasks (iii) and (iv) and the palmar grasp for the remaining. Successful attempts and failures were noted during the test. The user interface of the Freehand system based on the recording of shoulder movements was used. Elevation of the left shoulder induced a closing of the hand and depression of the shoulder leading to an opening of the hand. The appropriate ROM for shoulder control was determined prior to the measurements by instructing the tetraplegic person to fully elevate/depress the shoulder. In this experiment the user switched between the two grasp patterns by pressing a button integrated into the distal end of the shoulder joystick., but also other forms of switches, e.g. a switch in an armrest or a brain-switch [7] can be used.

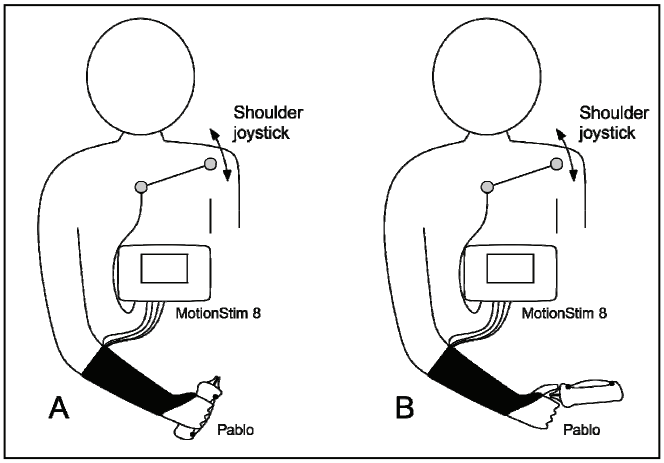

Figure 4. Setup for the force measurements of the two grasp patterns (A: extension/flexion forces of the palmar grasp, B: thumb flexion forces of the lateral grasp).

To investigate the reproducibility of the grasp patterns, the forearm sleeve was taken off the forearm and put on again after the GRT had been performed. The position of the FES electrodes inside the sleeve was fixed during all test sessions. The force measurements were done before and after the GRT and repeated independently a third time four days later.

III. RESULTS

With the personalized setup of the surface electrodes (Fig. 1) and the use of a specific stimulation profile a lateral pinch (Fig. 5) and a palmar grasp have been successfully generated (Fig. 6) in this person with a high SCI. After initial calibration of the shoulder position sensor the subject was able during all sessions to voluntarily control the degree of hand opening/closing by depression/elevation of her left shoulder. She was not only able to control the position of the hand from full extension to full flexion, but also to control the amount of force generated in a fully flexed position.

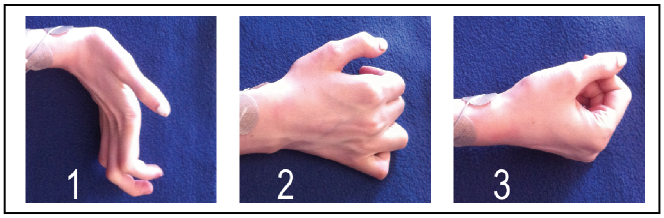

Figure 5. Three states of the sequence of the lateral grasp pattern. Subfigures 1-3 show the hand fully open, fingers closed with an extended thumb, and the full lateral pinch. The electrodes shown in the pictures were later covered with the forearm sleeve to maintain the correct positions during following montages.

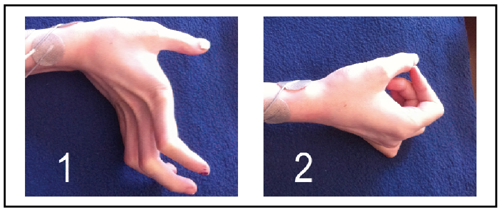

Figure 6. Two states of the palmar grasp pattern. Subfigure 1 shows the hand fully open and 2 the hand fully closed.

TABLE I. FORCES OF THE PALMAR AND LATERAL GRASP (IN N) MEASURED BEFORE, DIRECTLY AFTER AND 4 DAYS AFTER THE GRT.

	before GRT			**after GRT**			**4 days after GRT**		
Grasp	***Palmar***		***Lateral***	***Palmar***		***Lateral***	***Palmar***		***Lateral***
Move-ment	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.
mean	7.85	2.45	5.20	7.75	3.92	2.55	9.51	4.22	2.55
std	2.45	0.69	1.57	0.69	0.00	0.69	1.37	0.49	0.49

The mean force during the 10 consecutive measurements of the extension movement before the GRT was 2.45 ± 0.65 N, the force of the palmar grasp was 7.85 ± 0.65 N and the force of the lateral pinch was 5.2 ± 1.57 N, respectively. The force of the palmar grasp was stable during the three measurements (no statistical difference, $p>0.01$, t-test). However, the force of the lateral pinch decreased significantly ($p<0.01$, t-test) after the first measurement cycle (from 5.2 to 2.55 N, see Table 1 for details).

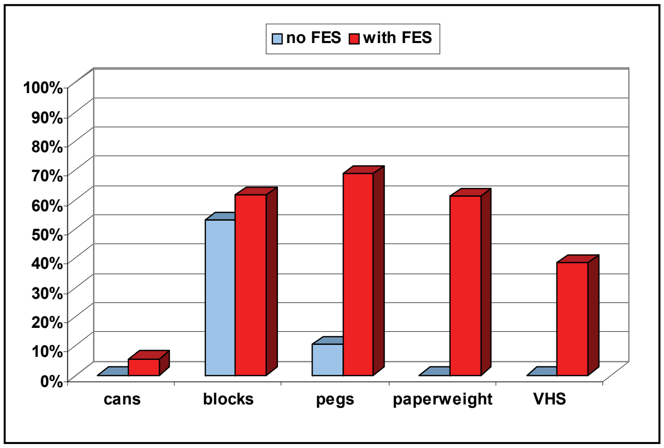

Figure 7. Overview of the percentage of completed attempts of different tasks of the Grasp-and-Release test with and without FES.

Without the grasp neuroprosthesis the subject failed completely to perform most of the functional tasks of the GRT with two exceptions: She was able to manipulate small and light objects (blocks, pegs), which she handled by trick movements. She could perform tasks for which higher grasp forces are needed (can, paperweight, VHS tape) only with the use of FES. With FES the mean rate of successfully completed tasks in relation to the overall number of attempts was 48% ranging from 6% to 68% depending on the specific task (Fig. 7). She was most successful in transferring the blocks, pegs and the paperweight (250 g) and was least effective in manipulating the can.

IV. DISCUSSION

A non-invasive grasp neuroprosthesis for restoration of two grasp pattern namely a lateral pinch and palmar grasp has been developed and the force and functionality of each grasp pattern has been quantitatively evaluated in a person with a high cervical SCI. Several components from existing neuroprosthesis have been integrated into one unique system with a strong focus on everyday use including an easy to handle electrode garment and a proportional shoulder control scheme. To overcome the problem of poor electrode-skin or electrode-sleeve contact observed in other non-invasive stimulation garments [8] our forearm electrode sleeve has been individually manufactured according to the forearm anatomy of the end user. The control interface of existing grasp neuroprostheses is often based on switch signals triggering a predefined timed stimulation sequence, e.g. hand opening or closing in a fixed timely manner [9]. However, in practical applications often quick correction commands need to be initiated by the user, which limits the usefulness of such digital control schemes. Hence, we implemented the non-timed direct proportional analog pulse width control via a shoulder position sensor equivalent to the Freehand system. In contrast to FES systems focusing on functional training of tetraplegic persons with substantial residual motor functions in the hands [10], our system has been specifically designed to be used by chronic SCI individuals with preserved shoulder function, but restricted elbow flexion and completely missing hand and finger movements.

A big advantage of implantable systems is their stable and reproducible application. Our test-retest results show that by using a dedicated forearm electrode sleeve reproducible grasp patterns and forces can be achieved also with surface electrodes. The mean forces of the lateral pinch achieved with the non-invasive grasp neuroprostheses are in the range of the implanted Freehand system (mean of 6.6 N with an interquartile range from 3.3 to 8.4 N [4]). The mean forces of the palmar grasp are significantly lower than those generated by the Freehand system (mean of 12 N with an interquartile range from 9.4 to 5.3 N), which is caused by the co-contraction stimulation scheme eliminating the need for misalignment-prone electrodes on the thenar of the hand [9]. Nevertheless, the end user was able to perform most of the functional tasks of the GRT with this amount of force.

The amount and the consistency of the force generation over days could likely be improved by an appropriate FES training. It is intended to provide the system to this SCI end user for a longer period so that a muscle training is automatically performed while the system is in use.

The high percentage of failures in some of the tasks of the GRT may be related to the user's inexperience since she used the neuroprosthesis in this configuration for the first time. Due to missing sensation of her hand she had to exclusively rely on visual feedback, which may additionally contribute to the moderate performance.

Due to substantial anatomical variances in persons with high SCI due to muscle atrophy, it has to be proven in future studies with a larger population, if the generation of the palmar grasp by stimulation of a branch of the N. medianus can be replicated.

Nevertheless, the non-invasive grasp neuroprosthesis developed in this work may serve as an easy to apply and inexpensive way to restore a restricted hand and finger function at any time after spinal cord injury. Additionally it may serve as a valuable test bed for more sophisticated control methods other than the shoulder joystick.

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REFERENCES

[1] K. D. Anderson, "Targeting recovery: priorities of the spinal cord-injured population," *J Neurotrauma,* vol. 21, pp. 1371-83, Oct 2004.

[2] V. R. L. Hentz, C, *Surgical Rehabilitation of the Upper Limb in Tetraplegia*. London, Edingburgh, New York: Saunders, W.B., 2002.

[3] R. Rupp and H. J. Gerner, "Neuroprosthetics of the upper extremity--clinical application in spinal cord injury and challenges for the future," *Acta Neurochir Suppl,* vol. 97, pp. 419-26, 2007.

[4] P. H. Peckham, M. W. Keith, K. L. Kilgore, J. H. Grill, K. S. Wuolle, G. B. Thrope, P. Gorman, J. Hobby, M. J. Mulcahey, S. Carroll, V. R. Hentz, and A. Wiegner, "Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study," *Arch Phys Med Rehabil,* vol. 82, pp. 1380-8, Oct 2001.

[5] B. Smith, P. H. Peckham, M. W. Keith, and D. D. Roscoe, "An externally powered, multichannel, implantable stimulator for versatile control of paralyzed muscle," *IEEE Trans Biomed Eng,* vol. 34, pp. 499-508, Jul 1987.

[6] K. S. Wuolle, C. L. Van Doren, G. B. Thrope, M. W. Keith, and P. H. Peckham, "Development of a quantitative hand grasp and release test for patients with tetraplegia using a hand neuroprosthesis," *J Hand Surg [Am],* vol. 19, pp. 209-218, 1994.

[7] J. Pfurtscheller, R. Rupp, G. R. Muller, E. Fabsits, G. Korisek, H. J. Gerner, and G. Pfurtscheller, "[Functional electrical stimulation instead of surgery? Improvement of grasping function with FES in a patient with C5 tetraplegia]," *Der Unfallchirurg,* vol. 108, pp. 587-90, Jul 2005.

[8] A. Prochazka, M. Gauthier, M. Wieler, and Z. Kenwell, "The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia," *Archives of physical medicine and rehabilitation,* vol. 78, pp. 608-14, Jun 1997.

[9] M. R. Popovic and T. Keller, "Modular transcutaneous functional electrical stimulation system," *Medical engineering & physics,* vol. 27, pp. 81-92, Jan 2005.

[10] M. R. Popovic, N. Kapadia, V. Zivanovic, J. C. Furlan, B. C. Craven, and C. McGillivray, "Functional electrical stimulation therapy of voluntary grasping versus only conventional rehabilitation for patients with subacute incomplete tetraplegia: a randomized clinical trial," *Neurorehabilitation and neural repair,* vol. 25, pp. 433-42, Jun 2011.