Efficacy of an Implanted Neuroprosthesis for Restoring Hand Grasp in Tetraplegia: A Multicenter Study

P. Hunter Peckham, PhD, Michael W. Keith, MD, Kevin L. Kilgore, PhD, Julie H. Grill, MS, Kathy S. Wuolle, OTR/L, CHT, Geoffrey B. Thrope, Peter Gorman, MD, John Hobby, FRCS, M.J. Mulcahey, OTR/L, Sara Carroll, PT, Vincent R. Hentz, MD, Allen Wiegner, PhD, For the Implantable Neuroprosthesis Research Group

ABSTRACT. Peckham PH, Keith MW, Kilgore KL, Grill JH, Wuolle KS, Thrope GB, Gorman P, Hobby J, Mulcahey MJ, Carroll S, Hentz VR, Wiegner A, for the Implantable Neuroprosthesis Research Group. Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study. Arch Phys Med Rehabil 2001;82:1380-8.

Objective: To evaluate an implanted neuroprosthesis that allows tetraplegic users to control grasp and release in 1 hand.

Design: Multicenter cohort trial with at least 3 years of follow-up. Function for each participant was compared before and after implantation, and with and without the neuroprosthesis activated.

Setting: Tertiary spinal cord injury (SCI) care centers, 8 in the United States, 1 in the United Kingdom, and 1 in Australia.

Participants: Fifty-one tetraplegic adults with C5 or C6 SCIs.

Intervention: An implanted neuroprosthetic system, in which electric stimulation of the grasping muscles of 1 arm are controlled by using contralateral shoulder movements, and concurrent tendon transfer surgery. Assessed participants' ability to grasp, move, and release standardized objects; degree of assistance required to perform activities of daily living (ADLs), device usage; and user satisfaction.

Main Outcome Measures: Pinch force; grasp and release tests; ADL abilities test and ADL assessment test; and user satisfaction survey.

Results: Pinch force was significantly greater with the neuroprosthesis in all available 50 participants, and grasp-release abilities were improved in 49. All tested participants (49/49) were more independent in performing ADLs with the neuroprosthesis than they were without it. Home use of the device for regular function and exercise was reported by over 90% of the participants, and satisfaction with the neuroprosthesis was high.

Conclusions: The grasping ability provided by the neuroprosthesis is substantial and lasting. The neuroprosthesis is safe, well accepted by users, and offers improved independence for a population without comparable alternatives.

Key Words: Activities of daily living; Electric stimulation; Hand; Neuroprosthesis; Rehabilitation; Spinal cord injuries.

AMONG THE MOST DEVASTATING effects of injuries to the cervical spine is the loss of hand function. The loss of arm and hand function is perceived by the large majority of persons with tetraplegia as the greatest loss associated with their injuries.[1] This loss severely limits their ability to live independently and to be gainfully employed, which greatly increases the extent, duration, and costs of care. As a result, improving hand function is an important rehabilitation objective for the more than 30,000 individuals with tetraplegia in the United States.[2]

Functional neuromuscular stimulation (FNS) is a technique in which paralyzed muscles are electrically stimulated to produce movement. Beginning in the late 1970s, FNS technology was applied to the muscles of the hand and forearm to provide hand-grasp function. Through initial studies of prototype percutaneous electrode technology,[3,4] FNS was found to be capable of providing fast, controllable, quiet, efficient, and functional movements.[5-8] Subsequently, an implanted neuroprosthetic hand-grasp system was developed to restore the ability to grasp, hold, and release objects to individuals with level C5 or C6 tetraplegia.[9-11]

This study was conducted to evaluate the safety, effectiveness, and clinical impact of a neuroprosthesis on individuals with spinal cord injuries (SCIs). We report here the results of a prospective, multicenter clinical trial of 51 persons with tetraplegia who received an implanted neuroprosthetic hand grasp system.

METHODS

The Neuroprosthetic Hand Grasp System

The neuroprosthesis used in this study, the NeuroControl FREEHAND® System,[a] provides unilateral hand grasp and release to tetraplegic individuals by using contralateral shoulder movements to generate control signals. The neuroprosthesis has both implanted and external components (fig 1). The

From the Department of Veterans Affairs, Rehabilitation Research and Development Services, Cleveland, OH (Peckham, Keith, Kilgore); MetroHealth Medical Center, Cleveland, OH (Peckham, Keith, Kilgore); Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH (Peckham, Keith, Kilgore); NeuroControl Corp, Cleveland, OH (Grill, Wuolle, Thrope); VA Maryland Healthcare System, Baltimore, MD (Gorman); University of Maryland Medical System, Baltimore, MD (Gorman); Salisbury District Hospital, Salisbury, UK (Hobby); Philadelphia Shriners Hospital, Philadelphia, PA (Mulcahey); University of Melbourne, Melbourne, Australia (Carroll); Stanford University Medical Center, Palo Alto, CA (Hentz); Palo Alto Veterans Affairs Health Care Service, Palo Alto, CA (Hentz); VA Boston Health Care System, West Roxbury, MA (Wiegner); and Harvard Medical School, Cambridge, MA (Wiegner).

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Reprint requests to P. Hunter Peckham, PhD, MetroHealth Medical Center, Hamann 601, 2500 MetroHealth Dr, Cleveland, OH 44109, e-mail: *pxp2@po.cwru.edu*.

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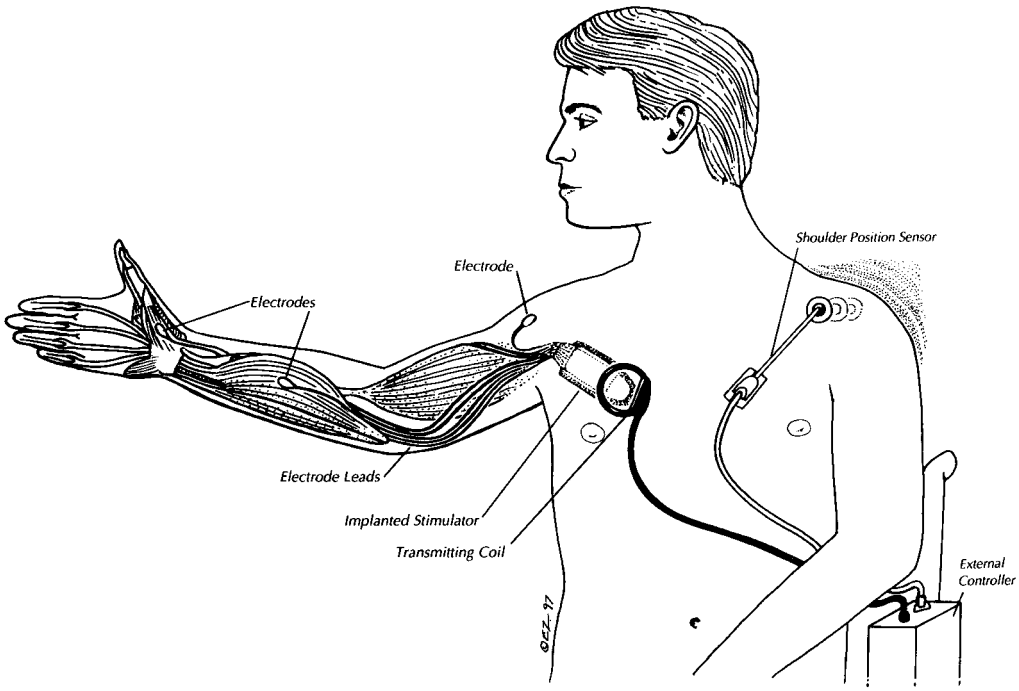

Fig 1. Location of the implanted neuroprosthesis and its components. (Reprinted by permission of NeuroControl Corp.)

implanted components consist of an implanted receiver-stimulator, epimysial electrodes, and interlead connectors. The external components consist of an external controller, a transmission coil that sends radio signals from the external controller to the implanted receiver-stimulator, and a shoulder position sensor with an integrated on-off switch.[9,10]

The user controls the neuroprosthesis with movements of the contralateral shoulder (either protraction-retraction or elevation-depression).[12] These movements are sensed by the shoulder position sensor and sent to the external controller, which transmits the signal to the implanted receiver-stimulator via the transmitting coil.[13] The implanted receiver-stimulator, in turn, sends an electrical stimulus through the leads to 8 epimysial electrodes surgically placed on hand and forearm muscles. Stimulation is delivered to produce coordinated muscle contractions by exciting the peripheral nerves that innervate the target muscles, resulting in the hand opening and closing. The command signal is proportional to the position of the contralateral shoulder, allowing the user to grade the movement and force of the hand grasp. The user can maintain a constant finger position and grasping force by disengaging the controller with a quick motion of the contralateral shoulder, which locks or unlocks the movement. The result is that users can acquire, hold, and manipulate both large and small objects of various weights and textures.

The system provides 2 types of grasp patterns: lateral pinch, in which the thumb closes against the side of the index finger, as when holding a key; and palmar grasp, in which the index and long fingers close against the thumb, as when holding a glass. Grasp and control patterns are customized by using a programming system.[14]

Target Population and Sample Selection

The target population for the neuroprosthesis are persons with cervical spinal injuries resulting in tetraplegia who have retained some motor function at the C5 and C6 myotome levels. These persons had at least antigravity volitional control in the elbow flexors, shoulder abductors and rotators, and wrist extensors (in those with C6 injuries), but none had voluntary control over either the intrinsic or extrinsic hand muscles. Inclusion criteria for participants in this study were: (1) a traumatic SCI resulting in tetraplegia at the American Spinal Injury Association (ASIA) C5 or C6 functional motor level[15] or ASIA impairment (formerly Frankel) grade A or B (International Classification grade 0, 1, or 2, O or Cu)[16] occurring at least 1 year before implantation; and (2) intact lower motoneuron innervation of key muscles of the forearm and hand, or their substitutes, as indicated by a grade 4 response to surface electrical stimulation. Key muscles are the thumb abductors, adductors, flexors, and extensors; and the finger flexors and extensors.

In addition, all participants had to be at least 16 years old or skeletally mature (as indicated by fused growth plates); have shoulder and elbow strength adequate to position the hand for functional activities; have good tolerance and stability seated in a wheelchair; be in good physical and mental health; be motivated; and be willing and able to return to the clinic for periodic evaluations.

Exclusion criteria included: cardiac pacemaker; history of chronic systemic infection or illness that increased surgical risk; uncontrolled spasticity; extensive and irreversible contractures in upper extremity joints; diabetes; immune disease; heart disease or cardiac arrhythmia; and breast masses with a high probability of being cancerous.

Surgical Procedure and Rehabilitation

Details of the surgical procedure for implanting the neuroprosthesis are published elsewhere and are summarized here.[9,17]

The receiver-stimulator and 8 epimysial electrodes were implanted in a single surgical procedure. The muscles stimulated to provide grasp were the extensor pollicis longus, flexor pollicis longus, adductor pollicis, abductor pollicis brevis, flexor digitorum profundus, flexor digitorum superficialis, and extensor digitorum communis. In some individuals, 1 electrode

was used to provide sensory feedback and was placed superior to the mid clavicle, in a region of normal sensation.[9,10] Augmentative and substitutional (tendon transfer) reconstructive surgery was performed in conjunction with neuroprosthesis implantation[17] to maximize voluntary function, both with and without the neuroprosthesis.[10,17-19] These procedures typically included transfer of the posterior deltoid to the triceps to provide elbow extension, and transfer of the brachioradialis to the extensor carpi radialis brevis to provide wrist extension.

Postoperatively, the treated arm was immobilized in a cast for 3 to 4 weeks to allow electrode encapsulation and wound healing.[10] After the cast was removed, muscle conditioning using the neuroprosthesis was initiated by programming it to cycle automatically through the stimulated grasp patterns for 8 hours while the participant was sleeping. Passive range-of-motion (ROM) exercises were often used in conjunction with muscle conditioning.

When all surgeries had healed completely and the treated muscles had the strength and endurance to begin performing functional tasks, the neuroprosthesis rehabilitation training and functional evaluation period began. Rehabilitation was typically completed between 3 and 6 months after implant surgery, though the exact timing and duration of this period depended on the extent of surgeries performed, as well as on individual participants' medical, social, and scheduling issues. During rehabilitation, participants were trained to operate the neuroprosthesis and to use it for functional activities. Rehabilitation was considered to be complete when users were satisfied with their ability to perform daily activities, or when they reached a plateau in proficiency, which usually occurred within 3 weeks.

Study Design

The study was conducted to evaluate the safety, effectiveness, and clinical impact of the neuroprosthesis on individuals with SCIs. The study was a multicenter, prospective cohort study with a minimum follow-up of 3 years postimplantation. Implementation and evaluation protocols were standardized across all study centers. The study was conducted at 10 centers (8 in the United States, 1 each in the United Kingdom and Australia). Because SCIs are highly variable across individuals and are rarely symmetric within a given person, the study was designed to have each participant serve as his/her own control. This design was possible because individuals were tested with the neuroprosthesis on and off.

The study was approved by the institutional review boards of all participating centers and adhered to the precepts in the Declaration of Helsinki. Written informed consent was obtained from all participants.

Main Outcome Measures

Study participants were evaluated according to standardized protocols to assess the impact of the neuroprosthesis on many dimensions of their disability. The National Center for Medical Rehabilitation Research (NCMRR) has identified 5 dimensions of disability: *pathophysiology* (". . .interruption of, or interference with, normal physiological and developmental processes or structures. . ."); *impairment* (". . .a loss or abnormality at the organ or organ system level. . ."); *functional limitation* (the restricted or lack of ability of an organ system to perform normally); *disability* (the restricted or lack of ability to perform tasks and roles to expected levels in physical and social contexts); and *societal limitations* (". . .restrictions attributable to social policy or barriers. . .").[20] Here, impairment was assessed by measuring pinch strength and active ROM, functional limitation with the Grasp-Release Test[21,22]; and disability with the Activities of Daily Living (ADL) Abilities Test,[10] the ADL Assessment Test, and a user satisfaction survey.[23] These measurements are described later. Because the neuroprosthesis is not intended to impact pathophysiology (ie, it does not cure the SCI) or directly impact societal limitations (eg, it will not remove societal barriers), these domains were not assessed.

Pinch force in both grasp patterns was measured with a pinch meter[b] modified to increase the platform size and to increase its sensitivity by a factor of 3 to detect small forces. ROM was measured with a standard goniometer.

In the Grasp-Release Test,[21,22] participants manipulated 3 objects by using the lateral pinch pattern (a peg, a paperweight, a fork) and 3 with the palmar grasp pattern (a 2.5-cm square block, a small can of juice, a videotape in a cassette). The force needed to lift the objects ranged from 0.1 to 4.4 newtons. The objects were to be grasped, moved over a barrier, and released, in a prescribed sequence of movements and within 30 seconds. Participants were scored as pass or fail on each object, with and without using the neuroprosthesis.[21,22] The order in which the objects were presented to the participant was randomized for every test session.

The ADL Abilities Test was developed to assess the impact of the neuroprosthesis on functional ability and independence.[7,10] All participants were trained to perform at least 6 ADLs. These required activities were selected from typical therapy goals for tetraplegic individuals with C5- and C6-level injuries and are: eating with a fork, drinking from a glass, writing with a pen, dialing a telephone, using a computer diskette, and brushing teeth. Additional activities were selected individually to meet each participant's personal goals. An occupational or physical therapist who had experience with SCI and who had specific training in administering the test provided the training in each activity. Every participant received training both with and without the neuroprosthesis, to achieve their maximum independence using each method. If necessary, participants were provided with splints or adaptive equipment to perform the task.

Users were scored according to the type of assistance required to complete each phase of a particular task. The assistance categories were ordered from least to greatest independence. The levels were: physical assistance from another person, use of adaptive equipment, use of orthotic assistance, use of self-assistance (eg, use of the mouth), and independence or requiring only the neuroprosthesis. The use of an orthotic device, worn throughout the day, was considered to be more independent than the use of individual pieces of adaptive equipment. Preference was also measured. Participants were asked whether they preferred to perform the task with or without the neuroprosthesis, and why. This test was designed to compare the impact of the neuroprosthesis on independence and task performance. All test sessions were videotaped for subsequent review and verification.

The ADL Abilities Test, though providing detailed and reliable information, is complex, requires highly trained therapists to administer, and may take as long as 2 weeks to complete. To simplify outcome measurements, a simpler test, the ADL Assessment Test, was administered to participants who enrolled later in the study. This test is primarily based on the degree of success in meeting goals established by each individual participant before neuroprosthesis implantation. Participants were scored by using the same ordinal assistance scale; however, tested activities were defined according to the goals set by the participant and therapist. Participants were asked to state whether they preferred to use the prosthesis for each task and were queried as to whether they met their goals. Therapists also recorded their perception as to whether the participants had met their goals.

For both the ADL abilities and assessment evaluations, improvement in independence was defined as requiring a lower level of assistance in completing each task. For example, if a participant required an adaptive splint and self-assistance (with the opposite hand or mouth) to acquire a fork and to eat without the neuroprosthesis but could acquire the fork in the lateral pinch and bring it to the mouth with the neuroprosthesis, independence was judged to have improved because the splint (as adaptive equipment) was no longer necessary to accomplish the task.

Participant satisfaction with the neuroprosthesis was assessed by using a 22-item user satisfaction survey.[23] Participants were asked about their general satisfaction with the neuroprosthesis, its impact on their lives and occupation, its impact on their need for assistance, and their regular use of the device. The survey used a Likert scale (strongly agree, neutral, strongly disagree) to categorize the responses.

Adverse events were monitored during the clinical study to evaluate the safety of the neuroprosthesis.

Data Collection

Data were collected at each site by occupational or physical therapists trained specifically to administer the tests. Videotapes of the Grasp-Release and ADL tests were reviewed to determine the consistency and accuracy with which the tests were administered. The therapists received feedback from the study monitor if differences in test administration were observed on the videotapes. Pinch force measurements and scores on the Grasp-Release Test were obtained preoperatively and at the end of the rehabilitation period. At each session, these tests were repeated 3 times, and the median value used in further analysis. ROM and ADLs were evaluated preoperatively and during the rehabilitation period, with single measurements at each session. The satisfaction survey was administered at least 6 months after completing rehabilitation. The long-term stability of grasp function was evaluated by repeating the pinch force and Grasp-Release tests at 1 year after rehabilitation. Long-term usage patterns were assessed through a follow-up survey administered to those participants who were at least 3.5 years postimplant. Functional outcome data were collected from August 1986 to August 1997, when the US Food and Drug Administration (FDA) approved the premarket approval application, with adverse events reported through August 2000.

Statistical Methods

Cohen's differences between proportions test[24] was applied to the Grasp-Release Test to evaluate the hypothesis that at least 75% of the participants would be able to manipulate at least 1 more object in the Grasp-Release Test with the neuroprosthesis and that at least 50% would be able to manipulate at least 3 more objects with the neuroprosthesis. Differences in lateral and in palmar pinch forces with and without the neuroprosthesis were analyzed with Wilcoxon's signed-rank test. Changes over time in Grasp-Release Test scores and median pinch force scores were assessed with McNemar's test. Alpha was set at .05. All tests were 1-tailed because function can only improve in these participants. All analyses were performed with the SAS statistical software package.[c]

RESULTS

Fifty-one individuals received an implanted neuroprosthesis and were studied (table 1). Of these, 82% were men, which is representative of the general SCI population. The median time between injury and enrollment was 4.6 years, and the median age at enrollment was 32 years. The median follow-up time was 5.4 years, with a minimum of 3.0 years.

Fifty individuals completed the rehabilitation training and evaluation phase of the study (table 2). One participant reported constipation associated with the use of the device. As a result, he was unable to complete rehabilitation training and was excluded from further functional testing. Repeated trials of device use and nonuse have indicated a relationship. The patient reported that this effect was also observed during surface stimulation exercise before implant. The clinical team continues to explore methods of bowel management for this individual.

The neuroprosthesis improved impairment measures in all participants tested. Pinch force in both grasp patterns increased significantly with the use of the neuroprosthesis (table 3). With the neuroprosthesis activated, all participants increased their pinch force in lateral pinch ($p < .001$), and 48 increased their pinch force in palmar grasp ($p < .001$). There was also a small but significant increase in median pinch force with the neuroprosthesis turned off when compared with the pinch force obtained before surgery. This increase is the result of the augmentative surgical procedures, such as tendon transfers for wrist extension and joint stabilizations.

All participants tested were able to achieve finger motion through stimulation, as measured through stimulated ROM measurements. No participant in this study had finger motion without the neuroprosthesis; therefore, any finger motion was an improvement over baseline.

Functional limitation was decreased in all but 1 participant (table 4). In the Grasp-Release Test, 49 of the 50 participants (98%) moved at least 1 more object with the neuroprosthesis ($p < .001$), and 37 (74%) improved by moving at least 3 more objects ($p < .001$) (table 5). These were significantly greater than the 75% and 50% targets established in the study hypotheses. As expected, many participants were able to manipulate the smaller, lighter objects (pegs, blocks) without the neuroprosthesis. Manipulation of larger and heavier objects was greatly improved with the neuroprosthesis.

Disability was reduced in all 49 participants tested (table 5), as measured by either the ADL Abilities or ADL Assessment

Table 1: Demographic and Clinical Characteristics of 51 Tetraplegic Participants Receiving an Implanted Neuroprosthesis to Restore Hand Grasp

Characteristic	Participants Receiving Implant
Gender, *n* (%)	
Men	42 (82)
Women	9 (18)
Injury level, *n* (%)*	
C5/0	15 (29)
C5/1	20 (39)
C6/1	2 (4)
C6/2	13 (26)
C6/3	1 (2)
Median time, injury to implant, yr (range)	4.6 (1.1–32.2)
Median age at implant, yr (range)	32 (16–57)
Median follow-up time, yr (range)	5.4 (3.0–13.9)

* The ASIA motor level is based on the presence of antigravity (3/5) strength in biceps and wrist extension for C5 and C6 levels, respectively. The International Classification (IC) for Surgery of the Hand in Tetraplegia identifies the number of forearm muscles that have at least 4/5 voluntary strength. Patients have an IC score of 1 if the brachioradialis meets this criterion, a score of 2 if the extensor carpi radialis longus also meets this criterion, and a score of 3 if, in addition, the extensor carpi radialis brevis meets this criterion.

Table 2: Study Participation

	Implant Surgery	Pinch Force	Grasp Release Test	ADL Abilities/ADL Assessment	Satisfaction Survey
Participated in study component	51	50	50	49	40
Medical condition preventing participation		1	1	1	
Data not available				1	9
Death					1
Implant removed					1
Total	51	51	51	51	51

Tests. Data were unavailable for 1 participant. The ADL Abilities Test was administered to 28 participants. Each participant was tested on 6 to 15 tasks (median, 9). All 28 participants improved in independence in at least 1 task, and 64% were more independent by using the neuroprosthesis in at least 3 tasks tested. All participants preferred to use the neuroprosthesis in at least 1 task tested, and 27 (96%) preferred to use the neuroprosthesis in at least 3 tasks. The ADL Assessment Test was administered to 21 participants, who were tested on 6 to 15 tasks (median, 8). In this test group, 20 (95%) participants reported that they had achieved their predetermined goals in at least 3 tasks and all reported that they were more independent in at least 3 tasks. Agreement between the therapist's and participant's assessment of goal achievement was excellent (table 5).

The satisfaction survey was administered to 40 participants (table 2). Of the remaining 11 participants, 9 could not be contacted, 1 had died, and 1 had had the implant removed. Five participants only reported on their usage, but did not complete the remainder of the survey.

User satisfaction with the neuroprosthesis was high. Ninety-seven percent (34/35) of participants would recommend the neuroprosthesis to others, and 91% (32/35) stated that the neuroprosthesis improved their quality of life (QOL). Device usage was also high (fig 2). Regular device usage for functional activities was reported by 34 of 40 participants, and 3 additional participants used the device regularly for exercise. Only 3 participants were nonusers, including the 1 participant with constipation related to the stimulation.

Long-Term Stability and Function

The long-term stability of the grasp was evaluated in 26 of the first 35 participants in the study (9 participants were unable to return for evaluation because of illness or travel limitations). There was a slight increase in the median pinch force with the neuroprosthesis and no change in pinch force without the neuroprosthesis (table 3). Most (19/26) of the participants showed no change in their ability to perform the grasp and release test with the neuroprosthesis. Of the remaining 7 participants, 4 had a decrease in grasp-release ability and 3 had an increase in grasp-release ability after 1 year.

Continuing long-term use of the neuroprosthesis was evaluated in 13 participants, who were a median of 5.1 years postimplant (minimum, 3.5yr). Eight of the participants had indicated that they used the device 7 days a week in the satisfaction survey, and all 8 remained 7-day-a-week users of the device 2 years later (table 6). However, 2 of the remaining 5 participants who were not 7-day-a-week users initially, had become nonusers, and an additional 2 participants used the device only for exercise.

Adverse Events

All 51 participants have been followed a minimum of 3 years postimplant at the time of this writing. There have been no cases of neuroprosthesis failure. In 1 participant, 1 channel on 1 implanted receiver-stimulator malfunctioned; however, the participant continued to use the neuroprosthesis with no functional deficit. In 3 of the first 10 participants, the receiver-stimulator had to be surgically repositioned after it rotated in the subcutaneous pocket, as occurs with cardiac pacemakers.[25] Subsequently, the implantation procedure was modified to include suturing the implanted receiver-stimulator to the subcutaneous tissue.

There were 3 electrode failures, 1 in each of 3 participants, among the 408 electrodes implanted as part of this study. Only 1 failure appeared to be the result of mechanical fatigue and use. This failure occurred after 2 years in an electrode implanted in the abductor pollicis brevis muscle of an active individual who propelled a manual wheelchair. The other 2 failures resulted from implant rotation, which pulled the electrode lead apart, and from a caregiver squeezing a skin eruption over the electrode and damaging it.

The number of serious adverse events was small. Six events occurred in 6 participants. Four participants experienced a

Table 3: Pinch Force (N) Among Tetraplegic Participants, With and Without the Neuroprosthesis Activated

		Grasp Force at Rehabilitation (n = 50)		Change in Grasp Force at 12mo (n = 26)	
Grasp Pattern	Preimplant (n = 44)	Without Prosthesis	With Prosthesis	Without Prosthesis	With Prosthesis
Lateral pinch					
Median	0.3	1.5	12	0.2	1.2
IQR	0–1.6	0–3.4	9.4–15.3	0.0–1.4	−1.3 to 4.4
Palmar force					
Median	0	0.4	6.6	0.0	0.8
IQR	0–1.5	0–1.6	3.3–8.4	−0.3 to 0.8	0.0–2.2

Abbreviation: IQR, interquartile range.

Table 4: Participants Passing the Grasp-Release Test, With and Without a Neuroprosthesis, by Grasping Pattern and Object

Grasp/Object	Preoperative (n = 44)	Rehabilitation (n = 50)	
		Without*	With*
Lateral grasp			
Peg	30 (68)	42 (84)	50 (100)
Weight	0 (0)	0 (0)	45 (90)
Fork	0	0 (0)	43 (86)
Palmar grasp			
Block	25 (57)	36 (72)	49 (98)
Can	7 (16)	13 (26)	39 (78)
Tape	3 (7)	9 (18)	36 (72)

NOTE. Values are *n* and percentage.
* With or without the neuroprosthesis activated.

localized infection at the site of an electrode. In 3 cases, the electrode was removed, the infection resolved, and, where necessary, the electrode was replaced. The fourth participant delayed seeking medical attention until the infection had progressed along some of the electrode leads such that explantation of the entire system was considered to be prudent. Localized infection in 2 of the participants described earlier and 2 additional cases of wound dehiscence occurred in the thenar eminence. Electrode placement in the thenar eminence was modified as a result of these incidents. One patient died of unrelated cardiac arrest 6 months postimplantation, and 1 patient died approximately 3 years postimplantation.

Other adverse events included swelling, discomfort, and skin irritation from surgery and from externally applied components; tendon adhesions; and other minor complications typically associated with surgery and rehabilitation. These adverse events were resolved with conventional treatment. One participant had a disrupted bowel routine that was associated with using the neuroprosthesis and was the only participant who did not complete the functional evaluations. Five participants reported an uncomfortable sensation over the implant (where the stimulus anode is located) during stimulation, and 5 others experienced inadvertent stimulation of the elbow flexors during hand activation, probably as a result of the pathway of the return current. In each of these cases, the stimulus was adjusted to produce adequate grasp function below the threshold for pain or inadvertent elbow flexion.

DISCUSSION

An implantable neuroprosthesis that provides hand grasp for C5- and C6-level SCI individuals has now completed a prospective, multicenter clinical trial and has received FDA premarket approval. Fifty of the 51 participants studied showed improved function when using the neuroprosthesis. No participant lost function as a result of the neuroprosthesis, and there were few adverse events. The functional enhancement provided by the neuroprosthesis is extensive and unachievable by any other means available to this group. It provides control in performing daily activities that results in improved function and independence. We believe that implantable neuroprostheses, in combination with tendon transfer surgery, should be considered as a standard course of rehabilitation for appropriate SCI candidates.

This study was designed to evaluate the impact of an implantable neuroprosthesis across 3 domains of the NCMRR disability spectrum: impairment, functional limitation, and disability. The impact of the neuroprosthesis on impairment and functional limitation was measured by using pinch force, ROM, and a Grasp-Release Test. When using the neuroprosthesis, all but 1 participant could manipulate at least 1 addi-

Table 5: Improvement in Functional Limitation and Disability Measures Among Tetraplegic Participants by Using an Implanted Neuroprosthesis

Measure of Disability	Participants Studied	Participants Improved ≥1 Task	Participants Improved ≥3 Tasks
Grasp-Release Test	50	49 (98)	37 (74)
Independence scores			
ADL Abilities	28	28 (100)	18 (64)
ADL Assessment	21	21 (100)	21 (100)
Total	49	49 (100)	39 (80)
Participants who prefer the neuroprosthesis for the task			
ADL Abilities	28	28 (100)	27 (96)
ADL Assessment	21	21 (100)	21 (100)
Total	49	49 (100)	48 (98)
Participants who reported meeting their goals			
ADL Assessment	21	21 (100)	20 (95)
Participants whose therapists rated goals as being met			
ADL Assessment	21	21 (100)	20 (95)

NOTE. Values are *n* and percentage.

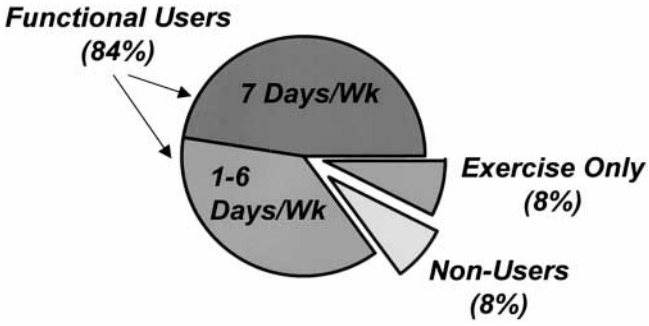

Fig 2. Regular use of the neuroprosthesis at home (n = 40).

tional object that they could not manipulate without the neuroprosthesis, and most could manipulate at least 3 additional objects. This result indicates that sufficient grasp force can be generated for the individual to pick up objects at least as heavy as 4.4 newtons. It also indicates that the grasp patterns provided are flexible enough to enable the participant to pick up objects of widely varying shape, such as a thin peg, a videotape, and a can.

The impact of the neuroprosthesis on functional limitation and disability was measured by using 2 ADL tests and a user satisfaction survey. The ADL Abilities Test was designed to ensure that each participant had equal training in performing activities both with and without the neuroprosthesis. Participants were required to perform the test at their optimum level of independence, even if they would not normally perform the activity in that manner at home. This approach ensured that any improvement in independence attributed to the neuroprosthesis was not biased by the resources and motivation of each individual. Instead, the independence provided by the neuroprosthesis was compared with the maximum independence that could be provided by any other means. All 28 participants who performed this test were more independent when using the neuroprosthesis. In some cases, participants had substantial reductions in their need for physical assistance to perform activities. In many cases, the neuroprosthesis eliminated the need for adaptive equipment. Even when independence was not directly affected by the neuroprosthesis for a particular activity, many participants indicated that they preferred to use the neuroprosthesis to perform the task. This preference suggests that some factor other than independence was provided by the neuroprosthesis. These factors, as identified by the participants, included decreased time in completing the task, increased ease in performance, and improved quality in performing the task.

The neuroprosthesis clearly does not affect every activity, nor is it intended to. In particular, manipulation of light objects, such as finger food, was often possible for participants to perform more easily without the neuroprosthesis, by using their existing tenodesis grasp or 2-handed manipulation. Because the neuroprosthesis can be turned off, the user can choose to perform tasks in the most convenient manner. The neuroprosthesis had the greatest impact on activities that required greater grasp force, such as eating with a fork, writing with a pen, and drinking from a glass.

More than 90% of the participants were satisfied with the neuroprosthesis, and most use it regularly. An improvement in QOL is difficult to assess across the entire population of study participants because QOL is affected by a myriad of factors other than those related to the neuroprosthesis, such as environmental factors and life events. However, many participants substantially improved their life circumstances after the implementation of the neuroprosthesis. Three participants were able to move out of nursing homes and into more independent living situations, and another regained the ability to take care of her own children. Many participants began additional schooling and, in a few cases, have returned to work.

Over 90% of the implant recipients indicated that they used the neuroprosthesis regularly for either function or exercise or both. This compares favorably with the reported usage rates for commercial FNS devices that are based on surface stimulation technology, which have reported usage rates of 17% to 50%.[26-28] Also, our long-term follow-up data show that daily use of the neuroprosthesis is maintained past 3 years. For those participants reporting 7-day-a-week use, the neuroprosthesis has become an integral part of their daily lives. Some individuals become nonusers, and the decision not to use the device appears to be related more to the personal goals of the participant than to the direct function provided by the neuroprosthesis. In the future, it may be possible to screen in advance those individuals who ultimately will become nonusers of the device,

Table 6: Long-Term Satisfaction and Usage With the Neuroprosthesis

Patient	Injury Level	International Classification	Implantation to Follow-Up Survey (yr)	Functional Usage: Satisfaction Survey (d/wk)	Functional Usage: Follow-Up Survey (d/wk)	Exercise Usage: Follow-Up Survey (Y/N)	Remain Satisfied	Less Satisfied	Not Satisfied Initially
A	C6	2	12.9	7	7	Y	•		
D	C5	1	6.9	7	7	Y	•		
G	C6	2	5.1	7	7	N	•		
H	C6	1	4.8	7	7	N	•		
I	C6	2	4.5	7	7	N	•		
J	C6	2	4.3	7	7	N	•		
K	C5	0	4.1	7	7	Y	•		
M	C6	2	3.5	7	7	N	•		
C	C6	2	7.0	4	5	N	•		
F	C5	1	6.1	4	0	N		•	
B	C5	1	7.9	2	0	N		•	
L	C6	2	3.7	1	0	Y		•	
E	C5	1	6.3	0	0	Y			•

Abbreviation: Y, yes; N, no.

but in this study, no clear pattern emerged that could predict usage a priori.

In summary, we found that everyone who received the neuroprosthesis obtained a usable hand grasp and showed improved independence. In most cases, the function provided by the neuroprosthesis was sufficient to lead to regular home use. Our follow-up results indicate that participants using the device regularly 6 to 12 months after implant will continue to be regular users of the device for the long term. If the participant shows little or no regular use initially, it appears that they may end up as nonusers of the device. In our study, no participant who started out as a daily user of the device quit using it after a few years. It will be important to continue to follow the usage patterns for these participants as they approach 10 to 15 years postimplant, but it appears that usage rates at 1 year are a good predictor of long-term usage.

The candidate selection criteria appeared in retrospect to be appropriate. Individuals with higher level injuries, such as ASIA level C4, could also benefit from a neuroprosthesis if it also provided upper arm function, such as elbow flexion.[29,30] Other researchers[31,32] have reported some preliminary laboratory findings on this level of injury. Individuals with injuries at the C7 level might also benefit from the added strength provided by the neuroprosthesis. These individuals were excluded from this study because other nonneuroprosthetic surgical methods can restore grasp and release in these persons. Clinical studies are currently underway to evaluate the effectiveness of a neuroprosthesis with these injury groups. Other factors, such as time postinjury, age, and sex may influence the ultimate impact of the neuroprosthesis to an individual's life, but a larger population study is required to evaluate these effects.

In this study, all screened candidates who fit the selection criteria were extended an opportunity to participate; however, only a portion of tetraplegic individuals are likely to be candidates for a neuroprosthetic hand grasp system.[33] Those who chose to participate in this study and to undergo a surgical implant were likely to be the candidates who had the greatest desire for independence. These individuals were likely to have the best outcomes in general, but we also found that some individuals we considered less motivated became excellent users of the neuroprosthesis. The fact that the neuroprosthesis provides a step to increased independence can, in and of itself, become a motivating factor. It is important to continue to identify the most important factors in candidate selection.

As with any implanted device, the time and monetary cost of implementation is an important consideration. It has been shown that the monetary cost of the neuroprosthesis used in this study can be recovered by a concomitant reduction in personal attendant services.[34] This analysis was based purely on the direct monetary costs, without considering any potential value provided by the neuroprosthesis in terms of improved QOL.

The surgical procedure and time involved in implanting and implementing the neuroprosthesis can be a disincentive to some potential candidates. Typically, about 3 months were required for implementation. One third of this time was required for healing after surgery, and the remainder was primarily associated with muscle conditioning using electric stimulation. Learning to use the neuroprosthesis is quite fast and can occur with 1 week of intensive therapy. Most individuals can manipulate objects within a few hours of donning the neuroprosthesis for the first time.

The low rate of both technical and medical incidents indicates that the implanted components are safe and can be properly installed by a trained surgical team. Implanting the neuroprosthesis does not adversely affect voluntary function, so if removal becomes necessary, there should be no loss of function compared with the individual's function before implantation. Reoperations were performed if the clinical team determined that adjustment of components of the implantable system or further reconstructive revisions to the hand were warranted. Most of the adverse incidents that required a secondary surgical procedure occurred in the first few participants at each center, suggesting that there was a learning curve for the surgical teams. As a result, we anticipate that a neuroprosthesis of this type is likely to be offered at regional centers with trained staff, rather than at widely distributed clinics. This pattern of care follows that of SCI care in general, in which regional centers with substantial experience in the treatment of these individuals can serve larger populations.[2] At the time of this writing, 35 surgical and 47 rehabilitation centers worldwide have been trained to implement the neuroprosthesis.

CONCLUSIONS

In this study of 51 selected tetraplegic participants treated with an implanted neuroprosthesis, the data support the conclusions that the neuroprosthesis: (1) substantially increases the number and variety of objects that participants can manipulate by hand; (2) increases lateral pinch and palmar grasp forces to functional levels; (3) improves participants' ability to accomplish more ADLs; (4) is well received by participants; and (5) is safe and has few complications.

This new technology offers an improved QOL and increased independence for a population without comparable alternatives. The results of this multicenter study indicate that an upper extremity neuroprosthesis provides substantial added function for individuals with C5- and C6-level SCI. We propose that neuroprosthetic intervention should be considered as an important option in the treatment of individuals with C5–6 tetraplegia.

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Suppliers

a. NeuroControl Corp, 8333 Rockside Rd, Valley View, OH 44125.
b. Model #PG30; B&L Engineering, 3002 Dow Ave, Ste 416, Tustin, CA 92780.
c. SAS Institute, SAS Campus Dr, Cary, NC 27513.