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Standing after Spinal Cord Injury with Four-contact Nerve-Cuff Electrodes for Quadriceps Stimulation

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Abstract

This report describes the performance of a 16-channel implanted neuroprosthesis for standing and transfers after spinal cord injury including four-contact nerve-cuff electrodes stimulating the femoral nerve for knee extension. Responses of the nerve-cuffs were stable and standing times increased by 600% over time-matched values with a similar 8-channel neuroprosthesis utilizing muscle-based electrodes on vastus lateralis for knee extension.

I. INTRODUCTION

Functional neuromuscular stimulation (FNS) is an intervention which has been shown to restore motor function and mobility after spinal cord injury (SCI) and to reduce secondary health complications by electrically stimulating intact motoneurons below the level of injury [1],[2]. In individuals with thoracic level SCI who maintain good upper extremity function, FNS has been employed to return standing and transfer function. One example of these standing and transfer systems (Table 1) uses an 8-channel Case Western Reserve University/Veteran Affairs (CWRU/VA) implanted receiver-stimulator (IRS-8) with muscle-based (epimysial and intramuscular) electrodes placed in or on the vastus lateralis (VL), gluteus maximus (GMAX) and semimembranosus (SMEM), and lumbar erector spinae (ESPIN) for knee, hip and trunk extension, respectively [3]–[5].

To date, this first-generation CWRU/VA standing/transfer system has been implanted in 18 subjects of various heights, weights, and levels of injury [6],[7]. In shorter and lighter subjects, maximum standing times of 10 minutes to 2 hours have been recorded, however taller and heavier neuroprosthesis recipients (in excess of 1.7 m or 80 kg) have typically been able to stand for less than five minutes [7]. Furthermore, smaller, lighter subjects are able to stand with up to 95% of their body weight (%BW) on their legs. In contrast, taller and heavier subjects place an average of 78 %BW on their legs and need to rely more on their upper extremities for support and balance [7].

Maximum standing time and body weight distribution are most often limited by insufficient stimulated knee or hip extension moment. One reason for this is that the epimysial electrodes used in the CWRU/VA system only recruit the muscle fibers of VL innervated by nerve branches near the implanted electrode. Incomplete recruitment of the total available muscle fiber pool in VL is compounded by the inability of the epimysial electrodes to activate other synergistic heads of the quadriceps (vastus intermedius (VI) and medialis (VM)) which would contribute to stimulated knee extension moment [3].

To more completely recruit the quadriceps, maintain knee extension, and improve maximum standing time and body weight distribution, a second-generation implanted standing neuroprosthesis is being developed and evaluated. The system (Table 1) consists of a 16-channel implanted stimulator-telemeter (IST-16) and monopolar four-contact CWRU spiral nerve-cuff electrodes around the distal branches of the femoral nerves [8]–[14].

This case study reports on a single subject who originally received the first-generation CWRU/VA IRS-8 standing system in December 1999 and was upgraded to a 16-channel system with bilateral femoral nerve-cuff electrodes in December 2005, thus affording a unique opportunity to objectively assess the performance of spiral nerve-cuff electrodes in comparison to the original epimysial system in a subject serving as his own historical and longitudinal control. Results in terms of peak isokinetic knee extension moment, maximum elapsed standing time, and body weight distribution are presented, as well as stability and recruitment properties of the nerve-cuff electrodes.

II. Methods

A. Subject Selection

The IST-16 system with bilateral nerve-cuffs was implanted in one male volunteer (age 53, 7 years post-injury) with motor-complete SCI (T6 level, ASIA A). The subject had previously participated in a study with the CWRU/VA IRS-8 system, so a direct comparison of the performance of the two systems could be made within a single individual. The subject was also one of the taller/heavier participants from the first study (height: 1.73 m, weight: 86.2 kg) who had insufficient knee extension to remain standing for long periods of time. During his peak performance with the IRS-8 system, the maximum recorded standing time for this subject was 4.5 minutes (at approximately two years post-implantation), and maximum %BW on the legs was 95% (at approximately three years post-implantation).

Before the implantation of the IST-16 system, this subject had not consistently utilized his muscle-based IRS-8 system for over one year. Because of this long period of reduced activity, it is likely that he had returned to his baseline physical status as he lost much of the benefit originally gained from using the IRS-8 system, such as increased muscle mass and reduced muscle fatigability. Therefore, it was possible to make a fair side-by-side comparison of the performance of the two systems at matched intervals post-implantation.

B. Implanted Stimulator and Nerve-Cuff Electrodes

After disconnecting and removing the IRS-8 stimulator of the original standing system, the IST-16 (Fig. 1a) was connected to five of the retained epimysial and intramuscular electrodes in ESPIN and SMEM bilaterally and the right GMAX. A broken epimysial electrode in the left GMAX (broken at approximately 4.5 years post-implantation) was replaced with an intramuscular electrode and connected to the IST-16. In place of the original epimysial electrodes on VL, two monopolar self-sizing four-contact spiral nerve-cuff electrodes (Fig. 1b,c) were installed on distal branches of the femoral nerve innervating the quadriceps. As best as it was possible to determine intraoperatively, the cuffs were placed on the femoral nerves distal to major branches for rectus femoris (RF) and sartorius (SART), both of which provide unwanted hip flexion, but proximal to the branches for VL, VM, and VI which provide knee extension without hip flexion. Eight independent channels of stimulation were connected to the bilateral nerve-cuff electrodes. The two remaining channels of stimulation were assigned to intramuscular electrodes inserted into the posterior portion of the adductor magnus (POST-ADD) bilaterally for additional hip stability.

C. Evaluation of Nerve-Cuff Stability

At regular intervals after cuff implantation (6, 14, and 36 weeks), stimulation parameters that achieved the maximum recruitment of the vastii without stimulation spillover to antagonist muscles or over-stimulation of agonist muscles were determined. For each contact in the nerve-cuff, current amplitude and pulse duration were varied for a 20 Hz biphasic charge-balanced stimulating waveform. Stimulation was monopolar with the capsule of the implant serving as the common anode to each electrode contact. Because the stimulator has one current source with a multiplexed output, there was a minimum 1 ms delay between stimulus pulses from any two channels, thus avoiding unpredictable recruitment effects due to superposition of electric fields generated at multiple electrodes. During stimulation, a physical therapist performed a stimulated manual muscle test (sMMT) to determine threshold and saturation pulse durations. Threshold was defined as the minimum pulse duration which generated a visible muscle contraction. Saturation was defined as the minimum pulse duration that generated a maximum muscle contraction but did not result in spillover to undesired muscles. Spillover to RF and SART was determined by palpation of their tendons at the hip with the subject supine, while the stimulated responses of the hip and back electrodes were characterized in side-lying. Stimulus current amplitude was fixed at 20 mA for the IRS-8 system and repeated for each of three current amplitudes (0.8, 1.4, and 2.1 mA) for each contact of the nerve-cuffs with the IST-16 system. Charge injection threshold for each nerve-cuff contact was calculated from these data as

$$Q_{th} = I \times PW_{th}, \quad (1)$$

where Q_{th} is the minimum charge injected in nC from an electrode contact to generate a visible muscle contraction, I is the stimulation pulse current amplitude (0.8, 1.4, or 2.1 mA), and PW_{th} is the threshold pulse duration in μ s. Threshold and saturation values were tabulated and compared over time.

D. Peak Isokinetic Knee Extension Moment

After implantation of each of the IRS-8 and IST-16 systems, the subject underwent a reconditioning exercise program consisting of high-intensity progressive resistance strength training and low-intensity progressive duration endurance training [3]–[6]. Upon completion of reconditioning exercise at 16 weeks post-implantation, knee extension moments were recorded isokinetically with a dynamometer (Biodex, Shirley, NY) at an extension rate of 30 deg/s using 3 second bursts of 16 Hz stimulation at parameters determined via the sMMT separated by 15 seconds of rest. With the IST-16 system, peak isokinetic knee extension moment was obtained for individual contacts within the nerve-cuff and all combinations of nerve-cuff contacts taken 2, 3, or 4 at a time in random order. Measurements were repeated 6 times for each configuration of contacts and peak extension moments were averaged and standard deviations calculated.

E. Maximum Standing Time and %BW Distribution

To eliminate any potential effects due to differences in practice, the subject completed identical standing and balance training with each system according to standardized protocols described elsewhere [3]–[6]. Patterns of stimulation for standing were constructed from parameters derived from a sMMT performed at a frequency of 16 Hz. This stimulation frequency was used on all contacts and electrodes to minimize fatigue and maximize standing duration. For the sit-to-stand transition, stimulus pulse durations on all electrodes and nerve-cuff contacts were ramped up to saturation over two seconds, and then maintained continuously for the remainder of the stand. Standing times were measured with a stopwatch from the beginning of the sit-to-

stand transition to the beginning of the stand-to-sit transition. %BW distribution was calculated from the initial steady state values of upper and lower extremity support forces measured with the subject standing with each foot on a separate biomechanics force platform (AMTI, Watertown, MA) and each hand on a separate instrumented parallel bar (JR3, Woodland, CA). Normal components of the ground reaction forces from the force plates and arm support forces from the parallel bars were compared to calculate the distribution of body weight on the legs.

Measures of standing time and body weight distribution were collected at the initiation of rehabilitation with each system (16 weeks post-implant) and repeated at 40 and 72 weeks post-implantation after further physical therapy and balance training with each neuroprosthesis. Additional elapsed time and %BW measurements were taken at 72 weeks post-implantation with the IST-16 system while standing without stimulation of the new intramuscular POST-ADD electrodes. These trials isolated the effects of the nerve-cuff electrodes and controlled for the potential confounding influence of the additional hip extensor muscles on standing performance by simulating the muscle set of the IRS-8 system. A two-tailed Student's t-test was used to compare the means of the three maximum standing times from each system.

III. Results

A. Nerve-Cuff Stability and Stimulation Parameters

For all contacts on both left and right nerve-cuffs, threshold data at 6, 14, and 36 weeks post-implantation are shown in Fig. 2. Stimulation thresholds in terms of injected charge appear to be consistent over time and exhibit little variability between measurements, indicating stability of the implanted components and maintenance of a consistent geometric relationship between the cuff and nerve.

It is important to note that all four contacts in each cuff were not used in the standing system. The sMMT revealed that contact 2 on the left side and contacts 3 and 4 on the right side recruited RF and SART and could cause hip flexion during standing. These contacts were therefore not included in the daily rehabilitative exercise regime or data collection sessions. It is also important to note that saturation data were not included in the analysis because of the ceiling effect imposed by the maximum pulse duration allowable by the IST-16 stimulator. That is, the pulse duration limit of the stimulation system (200 μ s) was often reached before contractile strength plateaued or spillover to other muscles was observed.

B. Peak Isokinetic Knee Extension Moment

Shown in Fig. 3 are peak isokinetic knee extension moments for left and right legs from the IRS-8 system during epimysial electrode stimulation (black bars) and from the IST-16 system during nerve-cuff stimulation (white bars). Also shown are peak isokinetic moments for all combinations of the two nerve-cuff contacts on the right side (contacts 1 and 2) and of the three contacts on the left side (1, 3, and 4) used during standing that produced isolated responses of the vasti. Peak isokinetic knee extension moment generated by each contact individually was equivalent to the single epimysial electrode response. Additional knee extension moment was generated by stimulating multiple contacts within the left nerve-cuff.

C. Maximum Standing Time and %BW Distribution

Displayed in Fig. 4 are maximum standing time (a) and %BW distribution on the legs (b) at 16, 40, and 72 weeks post-implantation for the IRS-8 (black bars) and IST-16 systems (white bars), as well as the IST-16 without the POST-ADDs that better simulates the actions of the IRS-8 system at the hips (gray bars). Because some nerve-cuff contacts recruited RF or SART, only cuff contacts 1, 3, and 4 on the left and 1 and 2 on the right were used during standing. To present a more complete description of the performance of the IRS-8 system, the maximum

standing time and %BW achieved over the five years the system was in use (prior to failure of the original left epimysial GMAX electrode) are displayed for comparison. At every time interval, the IST-16 system outperformed the IRS-8 system, and the mean of the three maximum stands with the IST-16 system (mean $\pm$ standard deviation = 741.6 $\pm$ 44.8 s) was significantly larger ($p < 0.001$) than that with the IRS-8 system (191 $\pm$ 61.5 s). Elapsed standing times exceeded the maximum achieved with the IRS-8 system even without the additional hip extension provided by the POST-ADDs.

IV. Discussion

These preliminary data indicate that the IST-16 system and nerve-cuff electrodes exhibit stable thresholds and produce sufficient knee extension moment for prolonged standing more than one year post-implantation. For this subject, the IST-16 system with nerve-cuff electrodes on branches of the femoral nerve appears to be outperforming the IRS-8 system with epimysial electrodes on VL. Any of the individual nerve-cuff contacts that were used in the system can produce at least as much knee extension moment as a single epimysial electrode on VL, and each of those contacts generates extension moment greater than the 35 Nm required for the sit-to-stand transition [15]–[19]. On the left side, combinations of two or three contacts produce larger extension moments than any individual contact. This suggests that individual contacts within the cuff may be selectively activating distinctly different regions of the femoral nerve such that, when multiple contacts are stimulated, they superimpose to produce a more complete contraction of a larger portion of the available motor unit pool. It should be noted that the selective behavior of these electrodes is dependent on their position relative to the nerve, which may explain why the left cuff shows this behavior while the right one does not, and why three of the eight cuff contacts were found to recruit RF and SART.

The IST-16 system with nerve-cuffs is also performing well functionally for this subject. Maximum standing times with the IST-16 system exceed those recorded at similar time intervals after implantation of the IRS-8 system, and the current maximum standing time achieved with the IST-16 system is nearly three times the maximum achieved over the five years of use of the IRS-8 system. During standing with the IST-16 system, the subject is able to support nearly 100% body weight on his legs, which suggests that he is able to remain upright on rigidly locked knees with the IST-16 system. While it is possible that the subject's prior experience with the IRS-8 system may have positively influenced his outcome with the IST-16 even after a year without use of the system, it is reasonable to expect this experience to impact only the rate of progress with the new system. The extra practice is unlikely to have contributed substantially to the threefold increase in maximum standing time evident with the IST-16 system. Furthermore, the maximum standing time and %BW are nearly the same during standing with the IST-16 system, with or without activation of the POST-ADDs, which suggests that the nerve-cuff electrodes are the primary reason for the improvement in standing performance seen with the new system. It should be noted, that the subject's body weight was not controlled during the study, and therefore could potentially confound the results. However, any fluctuations in body mass alone are also unlikely to explain the three fold increase in standing time observed with the IST-16.

Additional work with the nerve-cuffs should involve exploring the ability to selectively stimulate individual fascicles within the femoral nerve to recruit separate muscle populations with each contact. By separating out individual fiber populations within the muscle, it may be possible to stimulate some fibers to produce knee extension while other fibers rest, thus further reducing the effects of fatigue and allowing for even longer standing times. Also, other cuff electrode designs and stimulation paradigms should be explored, possibly including field steering, bipolar or tripolar electrode configurations, or different geometries such as a flat cuff cross-section to further improve selectivity and performance.

V. Conclusion

This single-subject case study indicates that activating the distal branches of the femoral nerve with a multi-contact spiral nerve-cuff electrode can improve the clinical performance of implanted standing neuroprostheses. Recruitment properties of implanted nerve-cuffs are stable over time, indicating the absence of relative movement, trauma or undesirable tissue reactions. Stimulated responses with nerve-cuff electrodes can be selective and produce greater joint moments than muscle-based electrodes.

For this subject, a 16-channel stimulation system with four-contact nerve-cuffs stimulating the femoral nerve produced standing times that were nearly 300% longer than had previously been accomplished with an 8-channel system with epimysial electrodes stimulating VL. The subject was able to support nearly 100 %BW on his legs when stimulation was delivered via the nerve-cuff electrodes, suggesting that he stood upright on rigidly locked knees with little need for upper extremity effort.

Isokinetic knee extension moments generated by each contact in the nerve-cuff were approximately equal to those generated via stimulation of VL with epimysial electrodes, and stimulation with combinations of multiple contacts from the left nerve-cuff generated larger moments than with any individual contact or with an epimysial electrode. This indicates that selective activation of different motor unit populations may be occurring with each contact. A degree of selectivity was also indicated by the ability to “tune out” undesired responses from RF and SART elicited by certain contacts within each cuff.

Data for this subject suggest that nerve-cuff electrodes provide a stable means of generating strong knee extension moments to allow for considerably longer standing times than epimysial electrodes. All evidence supports continued use of these nerve-cuff electrodes to restore function to individuals with spinal cord injury.

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Fig. 1.

(a) The IST-16 stimulator which was implanted in a subject with SCI to restore standing function. (b) A self-sizing four-contact spiral nerve-cuff electrode used on bilateral femoral nerves in this study to stimulate the quadriceps muscles for knee extension. (c) The unspiraled nerve-cuff. All four contacts and the lead wire are visible.

Fig. 2.

Average threshold charge injected and standard deviation on all four contacts of both right and left nerve-cuff electrodes.

Fig. 3.

Peak isokinetic extension moment for left and right knees at 16 weeks post-implantation. Averaged data and standard deviations are shown for epimysial electrodes on VL in the IRS-8 system as well as for nerve-cuff electrodes on the femoral nerve in the IST-16 system. Data for individual and combinations of nerve-cuff contacts that isolated the vasti are shown.

Fig. 4.

(a) Maximum standing time and (b) %BW on the legs at 16, 40, and 72 weeks post-implantation. Data are shown for the IRS-8 system, the complete IST-16 system, and the IST-16 system without stimulation of the POST-ADDs. Maximal values achieved with the epimysial IRS-8 system are presented for comparison. %BW data for 40 and 72 weeks post-implantation with the IRS-8 system (*) were unavailable.

Table 1

CWRU/VA Standing System Muscle Sets

Function	Standing System	
	IRS-8	IST-16
Trunk Stabilization	Erector Spinae	Erector Spinae
Hip Extension	Semimembranosus	Semimembranosus
Hip Extension	Gluteus Maximus	Gluteus Maximus
Knee Extension	Vastus Lateralis (muscle-based electrode)	Vasti (femoral nerve-cuff)
Hip Extension	————	Posterior Adductor Magnus