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Instrumented objects for quantitative evaluation of hand grasp

William D. Memberg, MS and Patrick E. Crago, PhD
VA Medical Center, Cleveland, OH 44106; Case Western Reserve University, Cleveland, OH 44106; MetroHealth Medical Center, Cleveland, OH 44109

Abstract—Two instrumented objects have been developed for quantitative assessment of functional tasks performed with the hand. These objects are useful for assessing neuroprosthetic hand grasp systems, and may also be useful in evaluating a variety of other upper limb disabilities and rehabilitation techniques. One object monitors grasp force and object orientation during palmar prehension, allowing simulation of a drinking task or of manipulating a book. The second object monitors grasp force during lateral prehension for simulating eating or writing tasks. The two objects provide tools to analyze how a subject uses a hand grasp neuroprosthesis to perform activities of daily living. The objects will also be useful in comparing different methods of controlling the neuroprosthesis and in evaluating future changes in the neuroprosthetic system. Assessment trials with these two instrumented objects were performed quickly in an outpatient clinic setting.

Key words: *electrical stimulation, FNS, functional neuromuscular stimulation, hand grasp, quadriplegia, task performance and analysis.*

INTRODUCTION

Individuals with C5/C6 level quadriplegia have had hand grasp/release abilities restored through the use of functional neuromuscular stimulation (FNS), providing improved function in activities of daily living (1–4). In the FNS hand grasp system (hereafter referred to as the "neuroprosthesis") developed in Cleveland (1), the user maneuvers a command/control source, typically a position transducer mounted at the shoulder or wrist, to send a command signal to an external microprocessor-based stimulator, which then sends a stimulation pattern to the muscles of the forearm and hand through either percutaneous electrodes or a multichannel implantable stimulator (5–7). The neuroprosthesis provides two selectable grasp patterns: lateral prehension (generally used for grasping small objects) and palmar prehension, typically used to grasp larger objects (1). The user can "lock" the device when a desired force level or grasp position (the span between the fingers and thumb) is reached by either making a quick movement of his or her shoulder or by pressing a switch. Once the neuroprosthesis is locked, the stimulation level is kept constant while the user moves around.

The development of devices that quantitatively assess the ability of a subject to perform tasks with the neuroprosthesis would be useful in verifying the improvement in function observed qualitatively. Existing instruments that measure grasp force (8–14) were inappropriate for our studies. Many of the devices were not commercially available, several had questionable accuracy, and most were too heavy to be held by individuals with quadriplegia.

An alternative method of measuring grasp force would be to mount sensors on the hand. Force sensors

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Address all correspondence and requests for reprints to: Patrick E. Crago, PhD, Rehabilitation Engineering Center, Department of Orthopaedics and Rehabilitation, MetroHealth Medical Center, 2500 MetroHealth Drive, Cleveland, OH 44109.

have been mounted on the thumb and fingers in research applications (15,16). At this time, however, the mounting and calibration procedures required for these devices are too time-intensive for rapid clinical evaluations to be performed with adequate accuracy.

This article describes the design and testing of two instrumented objects that monitor grasp force and object orientation during laboratory manipulation tasks. The neuroprosthetic system (1,5–7) and the assessment tests in which these objects were used (17) are described elsewhere.

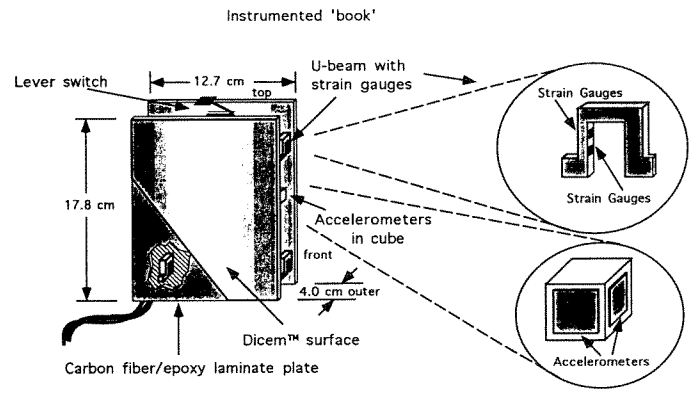

Figure 1a.
Drawing of the instrumented book. The high friction Dicem™ surface was used to prevent slippage of the object.

METHODS

Instrumented Objects Design

We developed two instrumented objects to quantitatively evaluate the neuroprosthesis in functional tasks. One object was shaped like a book, requiring the subject to use palmar prehension. This object provided information on grasp force and orientation of the object. Another object was shaped like a thin, rectangular beam, simulating a pen or fork. This was grasped using lateral prehension. Grasp force was monitored with this object.

The two objects had several common design specifications. The force transducers had to be able to measure forces up to at least 50 N, to cover the range of grasp forces produced by neuroprosthesis users (18). The desired resolution for a force sensor used in neuroprosthetic hand function has been estimated to be 0.1 N (15). The force measurement must be independent of the placement of the hand on the device. The force transducer also must not interfere with any of the other sensors mounted on the object. Since the objects were to be used in simulated functional tasks, the instrumented objects must be lightweight and hand-held. To allow the evaluations to be performed quickly, the devices should allow calibration prior to the arrival of the subject.

Instrumented Book

The book-shaped instrumented object consisted of two parallel plates separated by three U-shaped beams (**Figure 1a**). Each plate was made from a carbon fiber and epoxy laminate material, chosen for its high strength and low weight. The mass of each plate was 113 g and the total mass of the book was 301 g. The aluminum U-shaped beams, which were located in three of the four corners of the plates, had a pair of semiconductor strain gauges mounted on both sides of the thin section of each beam, making them sensitive to forces perpendicular to the plates. The strain gauges for each beam were connected to form two arms of a standard Wheatstone bridge to make the beam insensitive to lateral and rotational forces. The output of the bridge was connected to a three-stage amplifier, which included a low-pass filter with a cutoff frequency of 50 Hz. The total force on the book was obtained by summing the outputs of the three U-beams; the force on each was also available separately, allowing center of pressure to be calculated.

Since the book was to be picked up and moved around, a measurement of its orientation was desired. Initially, the orientation was monitored with a 3-D motion analysis system (17). To simplify this measurement, and to allow studies to be performed in an outpatient clinic, tilt sensors were mounted in the instrumented book. Two solid-state piezoresistive accelerometers (IC Sensors, Milpitas, CA) were placed between the plates so that they were perpendicular to each other, allowing measurement of the orientation of the book relative to gravity. The accelerometers had a mass of 1.8 g each, a size of 15.5 mm × 15.5 mm × 5 mm, a range of ±2 g, and an output that varied over a 360° rotation. The sensitive axis of one accelerometer was perpendicular to the plates while the other was perpendicular to the front edge of the book. Together, the accelerometers could be used to correct for the effect of gravity on the force output as the book was tilted. A low force lever switch was inserted between the plates at the top of the book and perpendicular to the top

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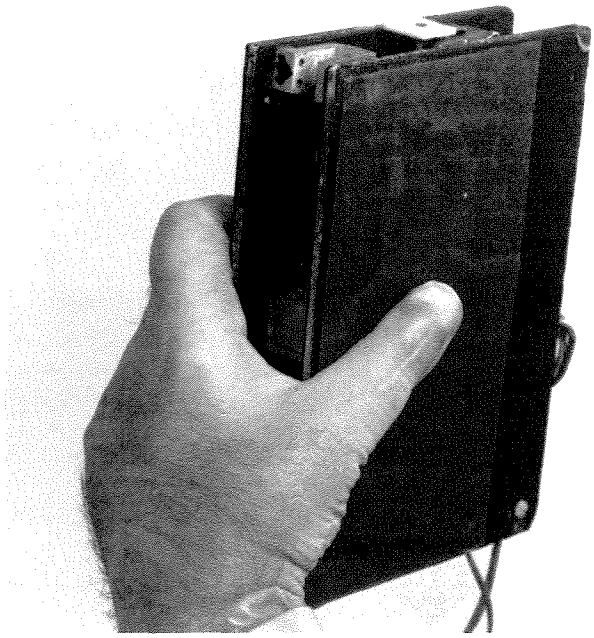

Figure 1b.
Photograph of a neuroprosthesis user utilizing palmar prehension to grasp the instrumented book.

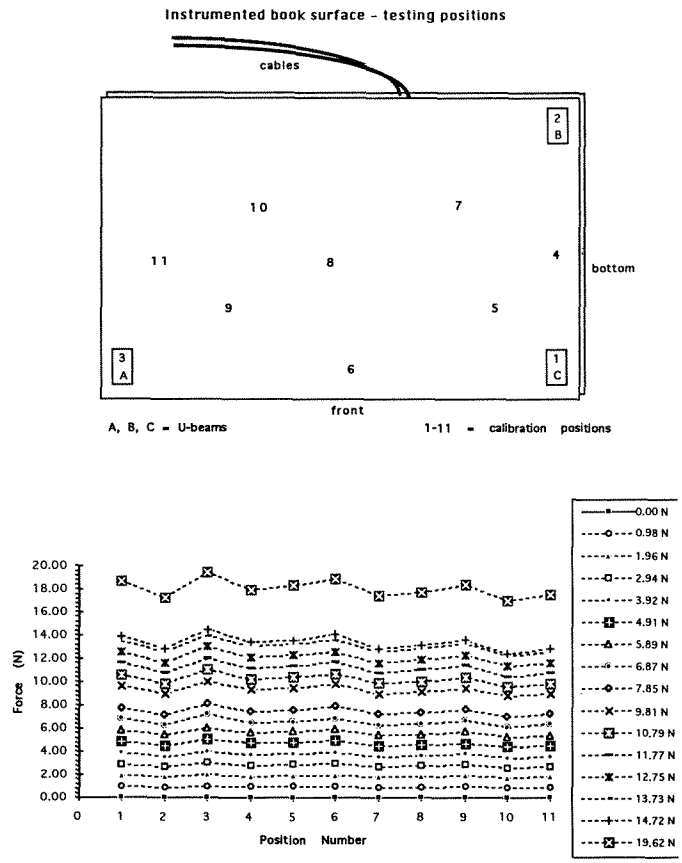

Figure 2a.
The variation in the instrumented book perpendicular force output for each of the calibration positions shown, indicating the sensitivity of the force output to the location where the instrumented book was grasped. Masses of 50 to 1900 g were applied to each position.

edge of the book, to indicate when contact with the top was made. The outputs of the two accelerometers and the switch were used in analyzing functional tasks performed with the instrumented book. **Figure 1b** illustrates a neuroprosthesis user utilizing palmar prehension to grasp the instrumented book.

The accelerometers were connected to a temperature-compensated instrumentation amplifier circuit that included a low-pass filter with a cutoff frequency of 5 Hz. This low cutoff frequency dampened acceleration measurements resulting from vibrations or bumping of the object. The frequency components of accelerations due to arm movements have been estimated to be less than 5 Hz (19).

Calibration

The force output of the instrumented book was calibrated to determine the sensitivity to both perpendicular and transverse (shear) forces applied at various positions on the surface of the book. Twenty masses (50 to 1900 g, three trials each) were placed on its surface as it lay on a table to obtain the book's sensitivity to perpendicular forces. The resulting linear slope was −0.183 volt/N with a correlation coefficient of 0.9999. The valid grasping area (where the user was most likely to grasp) was defined by a trapezoidal area on the book surface encompassing the three U-shaped beams (**Figure 2a**). Fifteen masses (100 to 2000 g) were each placed sequentially at 11 locations distributed across the trapezoidal area to determine the sensitivity of the force output to the location of the applied force. The force output is shown in **Figure 2a**. The standard deviation of the force output ranged from 4.2 to 5.1 percent of the mean force for each mass.

Since we only wanted to have sensitivity to forces perpendicular to the plates, we also tested the sensitivity to off-axis forces (i.e., forces in the plane of the plates). Sensitivity of the instrumented book to shear forces was

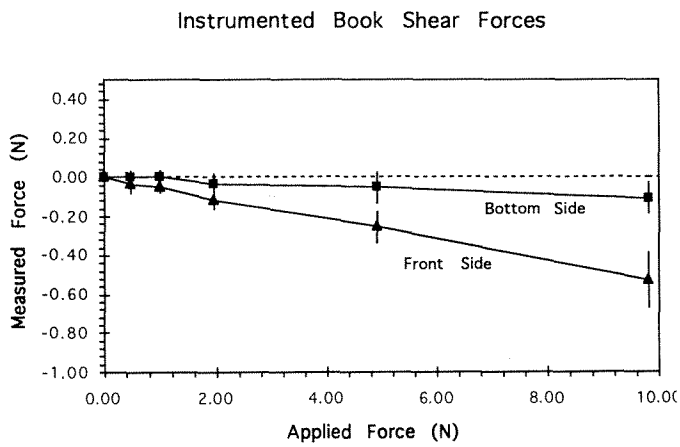

Figure 2b.
The variation in the instrumented book force output for different transverse forces applied to the front and bottom edges.

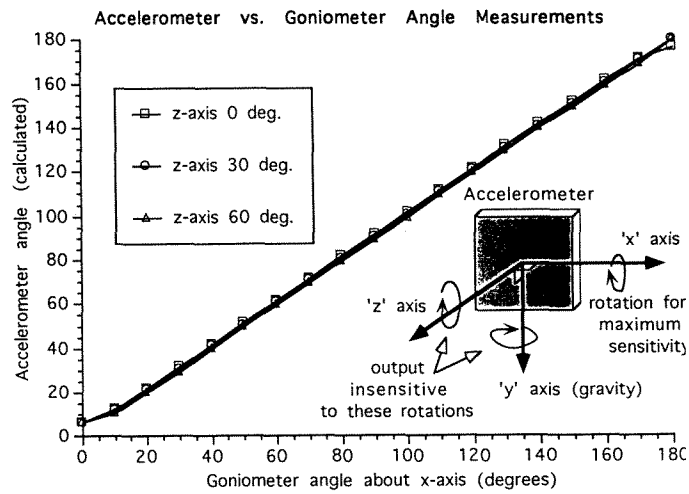

Figure 3.
Output of the accelerometer as it was rotated 180° around the x axis, as defined by the drawing. If the y axis corresponds to the direction of gravity, then the accelerometer is only sensitive to rotation about the x axis. Trials were performed with the accelerometer rotated at three different angles about the z axis, to demonstrate the insensitivity of the accelerometer to rotation around other axes.

measured by holding one of the plates vertically in a vise while weights were placed along the bottom and front edges of the other plate, producing forces parallel to the plane of the plate. The average output for three positions along the bottom edge and five positions along the front edge for masses of 50 to 1000 g is shown in **Figure 2b.** The output decreased with load at a slope of −5.3 percent of the equivalent perpendicular force for the front edge, and a slope of −1.1 percent for the bottom edge. The maximum output due to parallel forces was only 6.5 percent of the equivalent perpendicular force.

The accelerometers were calibrated by placing them in a jig that could be rotated 360° in two axes. Goniometers on the jig indicated the angle of rotation for both axes. Measurements were made as the accelerometer was rotated around the x axis (**Figure 3**) such that its sensitive axis (the z axis, perpendicular to the plane of the accelerometer surface) formed angles of 0° to 180° with gravity. Trials were repeated as the accelerometer was placed at different positions around the z axis, demonstrating the accelerometer's insensitivity to rotations that do not vary the position of its sensitive axis relative to gravity. A sample calibration is shown in **Figure 3**, in which the output was converted to an angle by calculating the inverse cosine of the accelerometer output. The relationship was linear with a slope of 0.985, a correlation coefficient of 0.999 and a standard error of 1.53°.

The force output was monitored as the surface of the instrumented book was rotated through a range of 180° relative to the direction of gravity in order to measure the effect the orientation of the book had on the output. The force output over the 180° range varied at a slope of 0.0078 N/°. This scale was used to provide gravity compensation for the force measurements in the functional tasks described below.

The "Drinking" Task

The instrumented book was utilized to examine the ability of a subject to use his/her palmar grasp to acquire a large object. In order to simulate a functional activity, the subject was asked to think of the object as a drinking glass, which was to be used to simulate taking a drink. At the start of a trial, the subject's neuroprosthesis system was off. The subject then turned the system on, selected the palmar grasp, gripped the glass, locked the neuroprosthesis, lifted the glass to his or her mouth and tilted it so that he or she could press the lever switch at the top of the glass on his or her chin, returned the glass to the table, unlocked the neuroprosthesis, released the glass, and turned the system off. By recording the information from the sensors on the glass, along with monitoring the neuroprosthesis information and data from a table contact switch, the task could be divided into a series of sequen-

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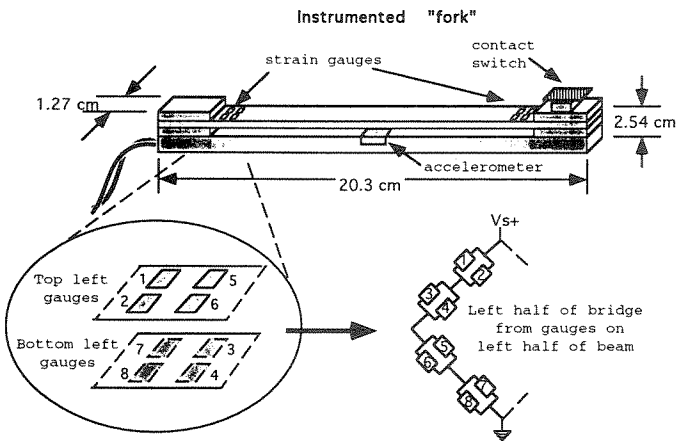

Figure 4a.
Drawing of the instrumented pen/fork.

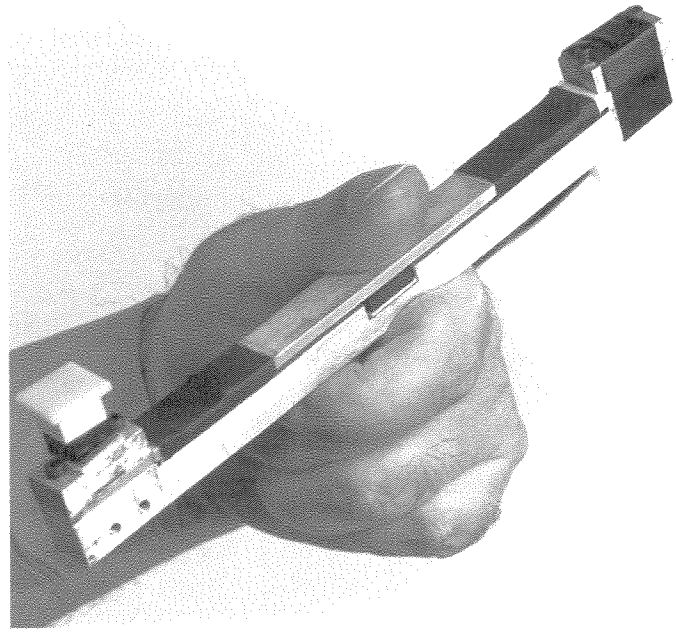

Figure 4b.
Photograph of a neuroprosthesis user utilizing lateral prehension to grasp the instrumented pen/fork.

tial states. Some of the states could not have been determined without the instrumented object. The data could then be analyzed to identify properties of the system and provide a quantitative measure of a subject's performance with the palmar grasp (17).

Instrumented Pen/Fork

Another instrumented object was designed that could simulate a pen or fork during functional testing. Two aluminum beams were bolted together at the ends (**Figure 4a**). One of the beams was 0.79 cm thick and acted as a supportive base for the second beam (the bending beam), which was 0.32 cm thick and constrained at both ends. Eight foil strain gauges were applied at each end (four on top and four on bottom) of the bending beam. In each set of four gauges, two adjacent gauges were connected in parallel and then connected in series to another parallel pair (**Figure 4a**). Each set of four gauges formed one arm of a standard Wheatstone bridge. This configuration measures the difference between the shear forces at two points at each end of the beam and thus allows measurement of force independent of the position along the beam at which the force is applied (20). The output of the full Wheatstone bridge is connected to a two-stage amplifier that includes a low-pass filter with a cutoff frequency of 50 Hz.

An accelerometer (identical to that used in the instrumented book) was placed in a slot in the support beam so that its sensitive axis was parallel to the normal force applied to the bending beam. This allowed a correction of the force output for the effect of gravity as the object was rotated. The accelerometer is connected to a temperature-compensated instrumentation amplifier circuit that includes a low-pass filter with a cutoff frequency of 5 Hz. A low-force contact switch was placed at one end, so that in situations where the object simulates a fork, there was an indication of when contact was made with the end of the fork. The mass of the instrumented pen/fork was 127 g. **Figure 4b** illustrates a neuroprosthesis user utilizing lateral prehension to grasp the instrumented pen/fork.

Calibration

The sensitivity of the instrumented pen/fork to perpendicular forces was calibrated by placing masses ranging from 50 g to 2000 g on the bending beam. The calibration curve for the average output for seven trials with each mass resulted in a linear slope of 0.313 volt/N with a correlation coefficient of 1.000. To evaluate the force output variation as force was applied at different positions along the beam, each mass was placed at seven equally spaced positions within a 7-cm section around its midpoint. The force outputs for the different masses and positions are shown in **Figure 5.** The force output varied

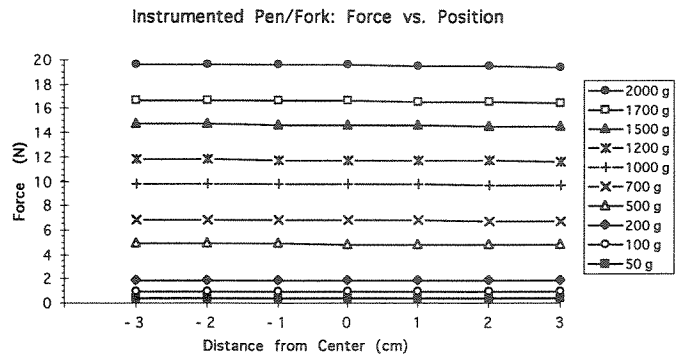

Figure 5.
Force output for each mass placed at seven positions along the pen/fork, demonstrating that the force output was independent of the location of the applied force.

slightly with the load position, with the largest error being 2.8 percent of the average output for a mass. The instrument output should not be sensitive to torsional forces. Sensitivity to torsional forces was examined by applying the masses at positions off the centerline of the long axis of the pen/fork and monitoring the output. The output varied by less than 1 percent when forces of up to 10 N were applied in this manner.

The accelerometer was calibrated using the same procedure described above for the instrumented book. Also, the force output was monitored as the long axis of the instrumented pen/fork was rotated through a range of 180° relative to the direction of gravity in order to measure the effect the orientation of the pen/fork had on the strain gauges. The force output over the 180° range varied at a slope of −0.0018 N°. This information was utilized to provide gravity compensation for the force measurements in the functional tasks described below.

The "Eating" Task

The instrumented pen/fork was utilized to examine a subject's ability to use his/her lateral grasp to acquire a small object. For this experiment, the subject was asked to think of the object as a fork, which would be used to simulate eating. At the start of a trial, the subject's neuroprosthesis system was off. The subject then turned the system on, selected the lateral grasp, gripped the fork, locked the neuroprosthesis, lifted the fork out of its holder, pressed the end of the fork against a force plate (the instrumented book lying on the table) to simulate the piercing of food, then brought the end of the fork to the mouth, pressed the switch at the end of the fork, returned it to its holder, unlocked the neuroprosthesis, released the fork and turned the system off. Similar to the instrumented book, a series of sequential task states was generated by comparing the timing information obtained from the measurements from the sensors on the fork, along with the neuroprosthesis information and data from a force plate and a table contact switch. This data could then be analyzed to identify properties of the system and provide a quantitative measure of a subject's performance with the lateral grasp (17).

Data Acquisition

The instrumented objects described above have been used in a series of tests to quantitatively evaluate the ability of persons with C5/C6 level quadriplegia to perform specific tasks with the neuroprosthesis. In addition to the sensors on the instrumented objects, data collected in

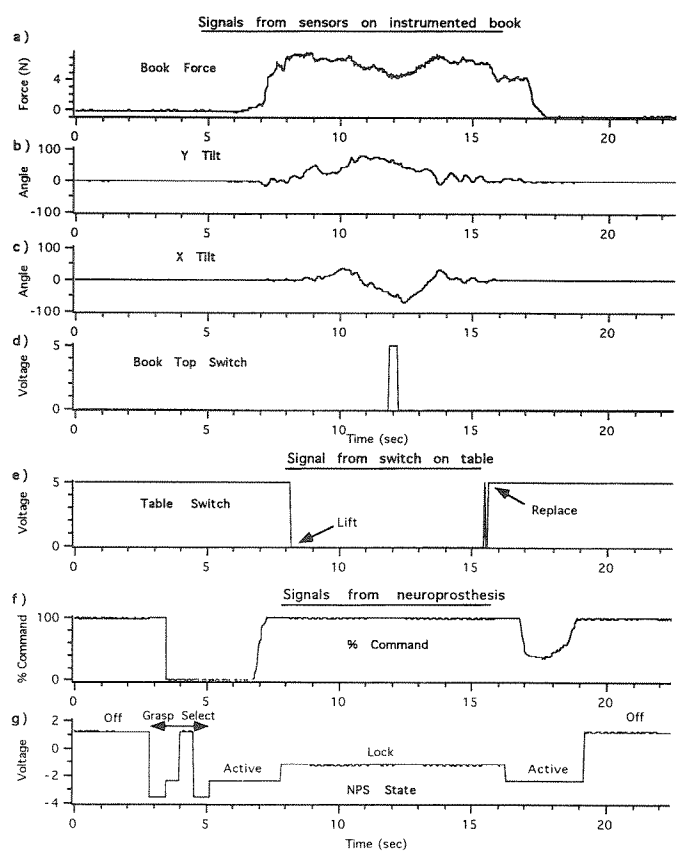

Figure 6.
Sample data from a drinking task.

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these experiments included the neuroprosthesis machine states and command information, and data from other external sensors and switches. All experiments were executed on a Macintosh IIfx computer utilizing a National Instruments 12 bit A/D board (National Instruments Corp., Austin, TX). The data were acquired at a sampling rate of 30 Hz using software written in the LabView™ programming environment.

RESULTS

Instrumented Book

An example of data from the "drinking" task is shown in **Figure 6.** The Book Force (*a*) data indicate when the glass was grasped and released, and how much force was applied to it. The orientation of the object is shown in the Y Tilt (*b*) and X Tilt (*c*) graphs. The Book Top Switch (*d*) data are used to determine when the glass was brought to the mouth. The Table Switch (*e*) information shows when the glass was lifted off the table and when it was put back down. The % Command (*f*) data indicate what level of command the subject utilized to perform the task. The state of the neuroprosthesis (off, active, locked, or select grasp modes) is displayed in the NPS State (*g*) graph.

In the trial shown in **Figure 6**, grasp force (*a*), which was adjusted for gravity, and command level (*f*) increased as the glass was picked up and decreased when it was put down. The table switch (*e*) indicated when the glass was lifted from the table (time=8.2 sec) and when it was returned to the table (t=15.6 s). At the point the object was picked up, the force applied to the book was 7.4 N and the command was at 100 percent. The glass was tilted (*b* and *c*) to greater than 80° from vertical as it was brought to the mouth to simulate drinking, at which point (t=11.9 s) the top switch was pressed (*d*). The Y Tilt information (*b*) was also used to adjust the force data for the effect of gravity. The neuroprosthesis state (*g*) was initially off, then the subject selected the palmar grasp (t=4.0–5.1 s), actively controlled her hand (t=5.1–7.8 s), locked at the desired command level to perform the task (t=7.8 s), then unlocked to release the glass (t=16.3 s), and turned the system off (t=19.2 s). Note that the grasp force varied significantly as the object was manipulated by the subject, but the force variations were not due to changing command levels.

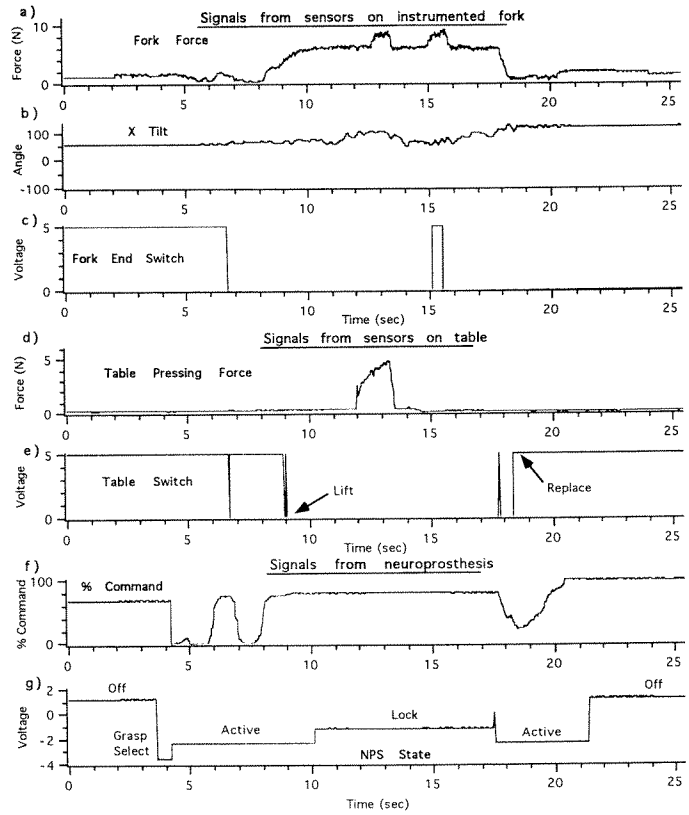

Figure 7.
Sample data from an eating task.

Instrumented Pen/Fork

An example of data from the "eating" task is shown in **Figure 7.** The Fork Force graph (*a*) indicates when the fork was grasped and released, and how much force was applied to it. The X Tilt (*b*) data can be used to subtract out the effect of gravity on the force reading. The Fork End Switch (*c*) indicates when the fork was brought to the mouth. The force used to simulate piercing a piece of food is shown in the Table Pressing Force graph (*d*). The Table Switch (*e*) information shows when the fork was lifted off the table and when it was put back down. The % Command (*f*) data indicate what level of command the subject utilized to perform the task. The state of the neuroprosthesis (off, active, locked, or select grasp modes) is displayed in the NPS State graph (*g*).

In the trial shown in **Figure 7,** grasp force (*a*) and command level (*f*) increased as the fork was picked up and decreased when the fork was put down. The table switch (*e*) indicated when the fork was lifted from the table (t=9.0 s) and when it was returned to the table

(t=8.4 s). At the point the fork was picked up, the command was at 100 percent and the force applied to the fork was 3.3 N, which increased to 6.0 N (at t=10.3 s) when the subject extended her wrist because of muscle length tension properties. The end of the fork was pressed against the force plate (*d*) with a force of 4.8 N to simulate piercing a piece of food (t=13.2 s), then was brought to the mouth to simulate eating, at which point (t=15.1 s) the switch at the end of the fork was pressed (*c*). There were small increases in fork force both times that it was pressed against an object (the table or the chin). The neuroprosthesis state (*g*) was initially off, then the subject selected the lateral grasp (t=3.6 s), actively controlled her hand (t=4.2–10.1 s), locked at the desired command level to perform the task (t=10.1 s), then unlocked to release the fork (t=17.5 s), and turned the system off (t=21.4 s). The tilt information *(b)* was used to adjust the force data for the effect of gravity.

DISCUSSION

The development of two instrumented objects has allowed the acquisition of quantitative information about a neuroprosthesis user's ability to perform simulated functional tasks. Both objects, combined with appropriate tests, allowed the data to be acquired quickly in a clinical setting, and could be used with left-handed or right-handed subjects and with any size hand. Each of the objects was calibrated prior to the subject's arrival, minimizing the time required of each subject and reducing the variability among subjects. Both prehension patterns (lateral and palmar) were evaluated.

The instrumented pen/fork was used successfully in the eating task with 12 neuroprosthesis users, and the instrumented book was successfully utilized by 11 users to perform the drinking task. One other neuroprosthesis user did not have enough strength in his palmar grasp to lift the glass and complete the task (17). The data from the successful trials for both the fork and glass allowed a separation of the tasks into sequential states, providing an identification of the more time-intensive portions of each task.

The addition of tilt sensors and contact switches to the instrumented book and pen/fork eliminated the need to use a 3-D motion analysis system in the present study. The accelerometers provided the desired orientation information and allowed for adjustment of the force output due to the effect of gravity, improving the accuracy of the force measurements. The contact switches provided additional timing information that was useful in state discrimination. Eliminating the 3-D motion analysis system allowed the experiments to be performed in the same room where FNS hand grasp subjects have their usual outpatient follow-up visits.

An additional instrumented object that measures grasp position and force simultaneously, which has been previously reported (21), was not as well-suited for these functional tasks. It lacked tilt sensors and contact switches needed for the task analysis. Also, since the instrumented book and pen/fork bore a closer resemblance to the actual objects that were being simulated, it was easier for subjects to perform the tasks appropriately.

Both the instrumented book and pen/fork were relatively insensitive to the location of the applied force, allowing both objects to be grasped quickly without the subject having to be concerned about placement of the fingers. In addition, both objects were insensitive to off-axis forces, assuring that only the perpendicular force was being acquired in these experiments.

Both instrumented objects will be useful in future evaluations of improvements in the hand grasp neuroprosthesis system. The objects can provide a quantitative comparison of subjects' abilities in task performance with different command controllers, such as shoulder transducers, wrist transducers, or a processed EMG signal. The incorporation of sensory feedback (22) or closed-loop control (23) into the hand grasp system should improve performance on functional tasks, which can be documented with the instrumented objects. Although the instrumented objects were tested only an persons with spinal cord injuries, these devices should also be useful in studying other upper limb disabilities.

CONCLUSIONS

Two instrumented objects have been developed, which allowed quantitative evaluation of functional tasks that were performed with a neuroprosthetic hand grasp. Evaluations can be done with the objects held in either the left or right hand and utilizing either lateral or palmar prehension. The objects allowed previously designed experimental assessments, such as eating and drinking tasks, to be performed quickly in an outpatient clinic setting, with similar results to those obtained previously. The instrumented objects should allow future improvements in the neuroprosthetic system to be quantitatively documented.

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REFERENCES

1. Peckham PH, Keith MW, Freehafer AA. Restoration of functional control by electrical stimulation in the upper extremity of the quadriplegic patient. J Bone Joint Surg 1988:70-A(1):144–8.
2. Wijman CAC, Stroh KC, Van Doren CL, Thrope GB, Peckham PH, Keith MW. Functional evaluation of quadriplegic patients using a hand neuroprosthesis. Arch Phys Med Rehabil 1990:71:1053–7.
3. Handa Y, Hoshimiya N. Functional electrical stimulation for the control of the upper extremities. Med Prog Technol 1987:12:51–63.
4. Nathan RH. Control strategies in FNS systems for the upper extremities. Crit Rev Biomed Eng 1993:21(6):485–568.
5. Buckett JR, Peckham PH, Thrope GB, Braswell SD, Keith MW. A flexible, portable system for neuromuscular stimulation in the upper extremity. IEEE Trans Biomed Eng 1988:35: 897–904.
6. Smith B, Peckham PH, Keith MW, Roscoe DD. An externally powered, multichannel, implantable stimulator for versatile control of paralyzed muscle. IEEE Trans Biomed Eng 1987:34(7):499–508.
7. Keith MW, Peckham PH, Thrope GB, Buckett JR, Stroh KC, Menger V. Functional neuromuscular stimulation neuroprostheses for the tetraplegic hand. Clin Orthop 1988:233:25–33.
8. An KN, Chao EYS, Askew LJ. Hand strength measurement instruments. Arch Phys Med Rehabil 1980:61:366–8.
9. Bechtol CO. The use of a dynamometer with adjustable handle spacings. J Bone Joint Surg 1954:36-A:820–4.
10. Helliwell P, Howe A, Wright V. Functional assessment of the hand: reproducibility acceptability, and utility of a new system for measuring strength. Ann Rheum Dis 1987:46:203–8.
11. Hermsdörfer J, Mai N, Marquardt C. Evaluation of precision grip using pneumatically controlled loads. J Neurosci Meth 1992:45:117–26.
12. King JW, Berryhill BH. A comparison of two static grip testing methods and its clinical applications: a preliminary study. J Hand Ther 1988:Oct– Dec:204–8.
13. Solgaard S, Kristiansen B, Jensen JS. Evaluation of instruments for measuring grip strength. ACTA Orthop Scand 1984: 55:569–72.
14. Tcheng P, Elliot J. Hand-strength meter. NASA Tech Briefs 1987:April:80.
15. Crago PE, Chizeck HJ, Neuman MR, Hambrecht FT. Sensors for use with functional neuromuscular stimulation. IEEE Trans Biomed Eng 1986:33(1):256–68.
16. Jensen TR, Radwin RG, Webster JG. A conductive polymersensor for measuring external finger forces. J Biomech 1991:24:851–8.
17. Burelbach JC, Crago PE. Instrumented assessment of FNS hand control during specific manipulation tasks. IEEE Trans Rehabil Eng 1994:2(3):165–76.
18. Hines AE, Owens NE, Crago PE. Assessment of input-output-properties and control of neuroprosthetic hand grasp. IEEE Trans Biomed Eng 1992:39(6):610–23.
19. Hollander JB. Integration of functional neuromuscular stimulation control of elbow extension and hand grasp (Thesis). Cleveland, OH: Case Western Reserve University, 1993.
20. Perry CC, Listner HR. The strain gage primer. New York: McGraw-Hill Book Co., 1962:230.
21. Memberg WD, Crago PE. A grasp force and position sensor for the quantitative evaluation of neuroprosthetic hand grasp systems. IEEE Trans Rehabil Eng 1995:3(2):175–81.
22. Van Doren CL, Riso RR, Milchus K. Sensory feedback for enhancing upper extremity neuromuscular prostheses. J Neuro Rehabil 1991:5:63–74.
23. Crago PE, Nakai RJ, Chizeck HJ. Feedback regulation of hand grasp opening and contact force during stimulation of paralyzed muscle. IEEE Trans Biomed Eng 1991:38(1):17–28.