

An analysis of the input-output properties of neuroprosthetic hand grasps

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Abstract—We measured the input-output properties of the hand grasps of 14 individuals with tetraplegia at the C5/C6 level who had received an implanted upper limb neuroprosthesis. The data provide a quantitative description of grasp-opening and grasp-force control with neuroprosthetic hand grasp systems. Static properties were estimated by slowly ramping the command (input) from 0 to 100%. A hand-held sensor monitored the outputs: grasp force and grasp opening. Trials were performed at different wrist positions, with two different-sized objects being held, and with both grasp modes (lateral and palmar grasps). Larger forces were produced when grasping larger objects, and greater opening was achieved with the wrist in flexion. Although active grasp force increased with wrist extension, it was not significant statistically. Lateral grasp produced larger forces than the palmar grasp. The command range can be divided into a portion that controls grasp opening and a portion that controls grasp force. The portion controlling force increased with spacer size, but did not depend significantly on grasp mode or wrist position. The force-command relationships were more linear than the position-command relationships. Grasp opening decreased significantly over a one-year period, while no significant change in grasp force was observed. These quantitative descriptions of neuroprosthetic hand grasps under varying conditions provide useful information about output capabilities that can be used to gauge the effectiveness of different control schemes and to design future control systems.

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INTRODUCTION

Individuals with C5/C6 level tetraplegia can have hand grasp and release restored by Functional Electrical Stimulation (FES) via an implanted neuroprosthesis (1). The device improves these individuals' functions in activities of daily living (2). Numerous factors affect the quality of the hand grasp of a neuroprosthesis user, including electrode placement, control method, physiological characteristics, and neuroprosthesis characteristics. To optimize the hand grasp patterns, it is necessary to quantitatively evaluate the outputs of the system (i.e., the force and opening of the hand) and determine their relationship to the input of the system (i.e., the command signal) from an external transducer (**Figure 1**). We developed a series of tests to quantify and evaluate these factors (3). These tests provide the foundation for the current study in a larger user population.

METHODS

Subjects

Experiments were performed on 14 individuals (11 male, 3 female) with tetraplegia at the C5/C6 level who had received an implanted hand grasp neuroprosthesis (**Table 1**). Several had tendon transfer surgery in conjunction with the implant surgery to augment their voluntary capabilities. These tests were done as part of their

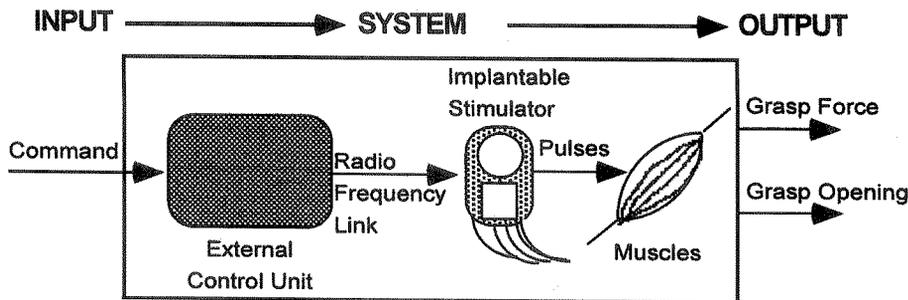


Figure 1.

A block diagram displaying the input (command from an external transducer) and outputs (grasp opening and force) of the neuroprosthetic system.

routine outpatient clinic visits, which included an initial rehabilitation visit soon after the surgery and follow-up visits approximately 6 mo and 1 yr later. Eight completed all three visits; of the remaining six, four had completed their rehabilitation prior to the start of this study, and two did not complete the follow-up visits.

Neuroprosthesis

The neuroprosthesis provides two selectable grasp modes (patterns): lateral prehension, generally used for grasping small objects; and palmar prehension, typically used to grasp large objects (4). A command source, usually a position transducer mounted at the shoulder or wrist, sends

a command signal to an external microprocessor-based control unit, which then sends a stimulation pattern to the muscles of the forearm and hand through an eight-channel implantable stimulator as shown in **Figure 2** (5,6). The users modulate their grasp by moving the shoulder or wrist on which the position transducer is mounted. When the user reaches a desired force level or grasp opening (the span between the fingers and thumb), they can 'lock' the neuroprosthesis by either making a quick movement of their shoulder or by pressing a switch. Once the neuroprosthesis is locked, the stimulation level is kept constant while the user moves around.

Data Collection

An instrumented grasp sensor (**Figure 3**) measured grasp opening and force (7). Different-sized spacers were placed in the sensor to limit the extent of object compression, and thus simulated different-sized objects

Table 1.

Hand grasp neuroprosthesis subjects.

Subject	Level	Wrist	Date	Age	Test
A	C6 OCu:2	Yes	8/26/86	37	91.3
B	C5 O:0	No	7/11/91	28	33.1
C	C5 O:1	No	8/29/91	34	23.3
D	C6 OCu:2	Yes	7/30/92	57	13.9
E	C5 O:1	Yes*	8/20/92	28	13.0
F	C6 OCu:2	Yes	10/8/92	29	5.2
G	C6 OCu:2	Yes	1/20/94	53	4.1
H	C6 O:2	Yes	2/17/94	26	7.5
I	C5 O:1	Yes*	3/10/94	30	24.0
J	C6 O:2	Yes	1/12/95	24	6.0
K	C5 O:1	No	2/9/95	32	5.6
L	C5 O:0	Yes*	3/9/95	42	5.3
M	C5 O:0	No	4/20/95	57	3.2
N	C6 O:1	Yes	6/1/95	51	3.3

*Wrist extension due to Brachioradialis to Extensor Carpi Radialis Brevis tendon transfer.

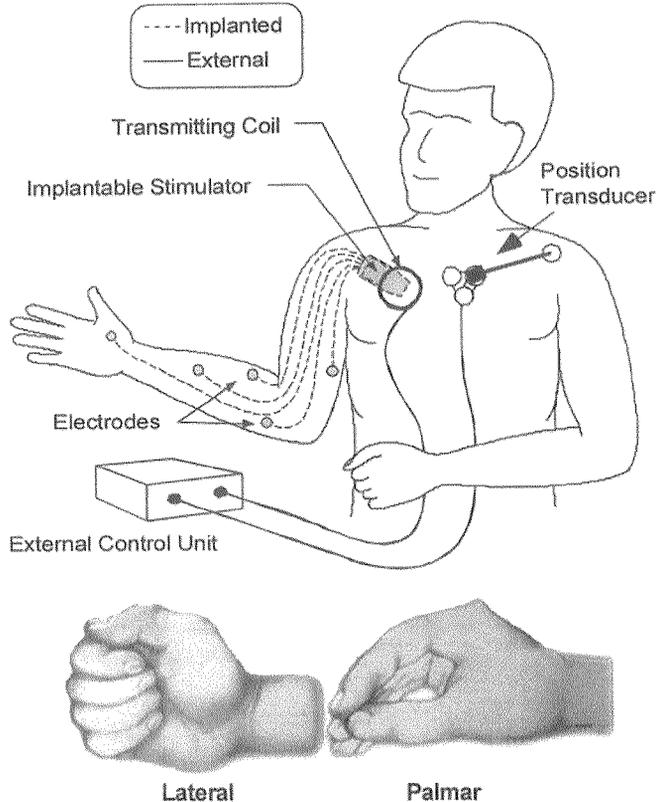


Figure 2.

A schematic of the neuroprosthesis showing the external control unit and the shoulder-mounted position transducer, along with the implanted stimulator and electrodes. Illustrations of lateral and palmar prehension are also shown.

being grasped. Grasp force was developed by contact with the spacer. We used two spacers in this study: a small spacer, 3 mm-thick, allowed a minimum grasp opening (from thumb to finger) of 1.3 cm (about the size of a pen); a large spacer, which was 3.4-cm thick, allowed a minimum grasp opening of 4.4 cm (about the size of a juice can). The same device was used for both lateral and palmar grasps. Since the device was handheld, the effect of wrist position on hand grasp could be evaluated.

The command signal information was obtained from the external control unit through an electrically isolated interface module. All experiments were executed on a Macintosh IIfx computer utilizing a 12-bit A/D board. The data were sampled at a 100 Hz rate with a custom data acquisition program.

Test Descriptions

In these tests, the system outputs (grasp opening and force) and the system input (command) were measured as the command signal was increased linearly from zero

percent to 100 percent over a 10-second interval. Separate measurement trials were performed for lateral and palmar grasp, with both the small and large spacer, and with the wrist at its maximum flexed position and its maximum extended position (if the user had voluntary wrist control). Since these individuals did not have voluntary wrist flexion, they were instructed to allow gravity to flex their wrists during the flexion trials. For the wrist-extended trial, the individuals with voluntary wrist control were instructed to maximally extend their wrists. One trial was performed for each set of conditions due to time constraints. The wrist angle was controlled by the user and was not constrained by a splint in either the flexion/extension or radial/ulnar planes.

Grasp force and grasp opening (position) were plotted versus command to display the static input-output properties for each subject's grasps, and these curves were characterized quantitatively with respect to position control and force control. The position control region was defined as the portion of the command range from zero until an increase in force of greater than 0.2 N, the force resolution of the grasp sensor (8), was recorded. The force control region began at this point and extended to the maximum command (100 percent).

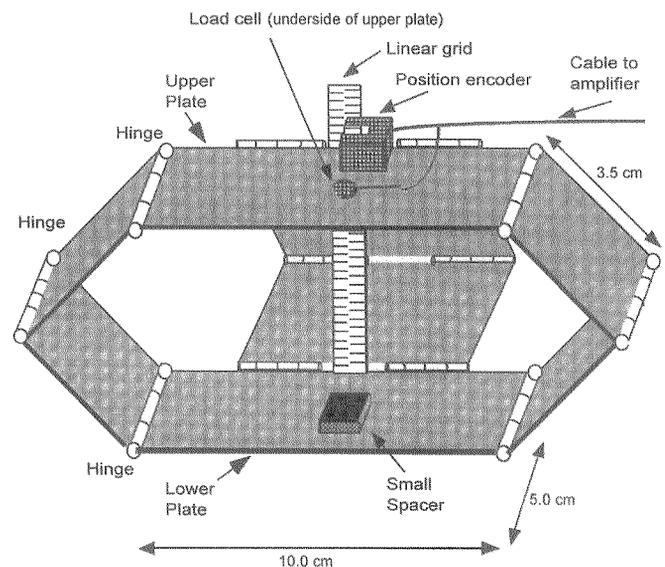


Figure 3.

Instrumented grasp sensor with optical grid and sensor to measure grasp opening, and load cell to measure grasp force. The object is held in the hand by grasping the upper and lower plates between the fingers and the thumb. The hinges maintain the upper and lower plates parallel to each other as the hand closes. Force is developed by the load cell contacting the spacer.

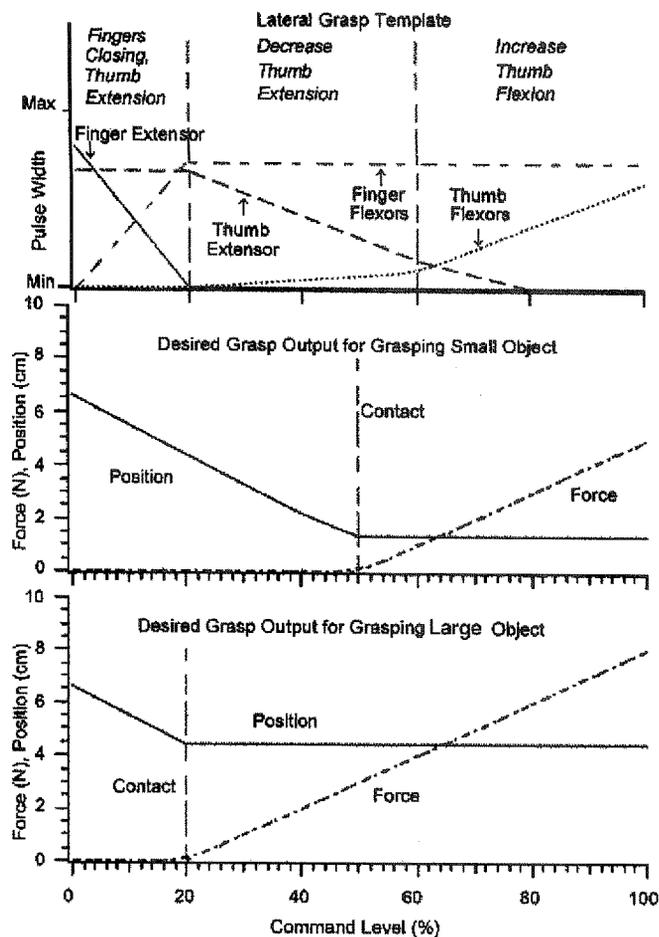


Figure 4a.

Ideal templates (left) and actual stimulus patterns and input-output properties (right) for lateral grasp. Stimulus patterns are shown at the top, and input-output properties are shown at the middle and bottom for small and large objects (spacers) respectively. The nonlinearity measures of the force and opening input-output curves were low (0.17 and 0.06 respectively for the small spacer, and 0.33 for force control with the large spacer). Nonlinearity was not calculated for position control for the large spacer, since position did not change.

The nonlinearities of position control and of force control were quantified separately for each grasp condition by single numbers, using a measure of nonlinearity that we developed previously (9). This nonlinearity measure compares a polynomial (fourth-order) curve fit of the data to a straight-line fit over the same command range. Since the measure quantifies slope differences, regions of the curve with high gains or deadbands produce higher nonlinearity values.

where m = the average slope between the end points,

C = command,

C_{\max} = the upper command level of the section,

C_{\min} = the lower command level of the section, and = derivative of the 4th order polynomial fit.

$$\text{nonlinearity} = \frac{1}{m^2 (C_{\max} - C_{\min})} \int_{C_{\min}}^{C_{\max}} \left(\frac{dy(c)}{dc} - m \right)^2 dc$$

where

m = the average slope between the end points,

C = command,

C_{\max} = the upper command level of the section,

C_{\min} = the lower command level of the section,

and $\frac{dy(c)}{dc}$ = derivative of the 4th order polynomial fit.

RESULTS

Stimulation templates for lateral and palmar grasps have previously been described by Kilgore, et al. (4). The templates for the two grasp types differ in the proportions of the command range that are allocated for finger closing and force production (Figures 4 and 5). The stimulation template for a lateral grasp, along with the idealized input/output curves (grasp templates) for a subject grasping a small and a large object are shown in Figure 4a. A recorded example for a specific subject is shown in Figure 4b for comparison. For either lateral or palmar grasp, the ideal grasp opening decreases linearly as the command level increases and the ideal grasp force increases linearly after contact occurs. To achieve the ideal lateral grasp, finger extensor stimulation decreases from maximum in the first 20 percent of the command range, while finger flexor stimulation increases and thumb extensor stimulation remains at maximum. This produces maximal grasp opening while the fingers curl in. In the middle 40 percent of the command range, finger flexor stimulation is constant, while thumb extensor stimulation decreases and thumb flexor stimulation increases to close the thumb onto the lateral aspect of the index finger. In the upper 40 percent of the command range, thumb flexor stimulation increases to increase grasp force once the thumb contacts the object. Since contact occurs sooner for a larger object, force increases earlier, even though the stimulation is the same.

The lateral grasp stimulation pattern created for subject L was modified from the template by including thumb abductor stimulation in the upper 20 percent of the command range to alter the direction of thumb force without decreasing force magnitude (Figure 4 right). With the small spacer in the grasp sensor, the input/output curve closely approximated the desired grasp template. The fingers and thumb closed, decreasing the grasp opening in the first half of the command range. After contact (48 percent command), force began to increase and generally continued to increase through the remainder of the command range. When the

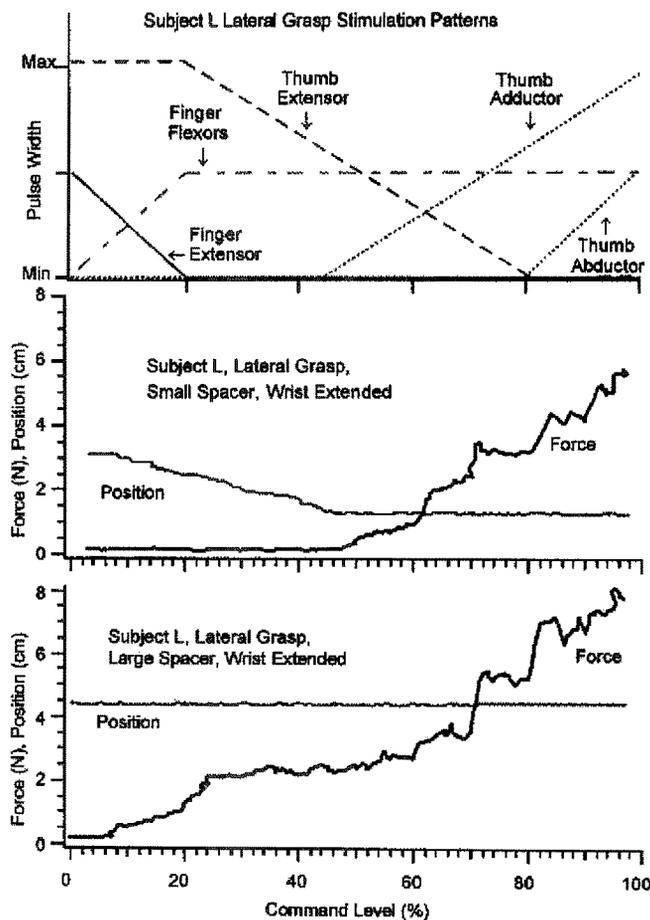


Figure 4b. Actual stimulus patterns and input-output properties for lateral grasp.

small spacer was replaced with the large spacer, the force began increasing earlier in the command range (around 8 percent command) and reached a higher force level. Since this subject's maximal grasp opening was smaller than the height of the large spacer, there was contact throughout the command range.

In the idealized palmar grasp stimulation template, shown in **Figure 5a** (4), thumb abductor stimulation remains constant at a high level throughout the command range, allowing the thumb to oppose the finger pads. Finger extensor stimulation decreases from the maximum in the first 25 percent of the command range, allowing the fingers to close from maximal extension. Finger extensor stimulation continues to decrease while finger flexor stimulation increases over the middle 50 percent of the command range, to close the fingers and start applying force. Finger and thumb flexor stimulation increases in the last 25 percent of the command range to increase grasp force.

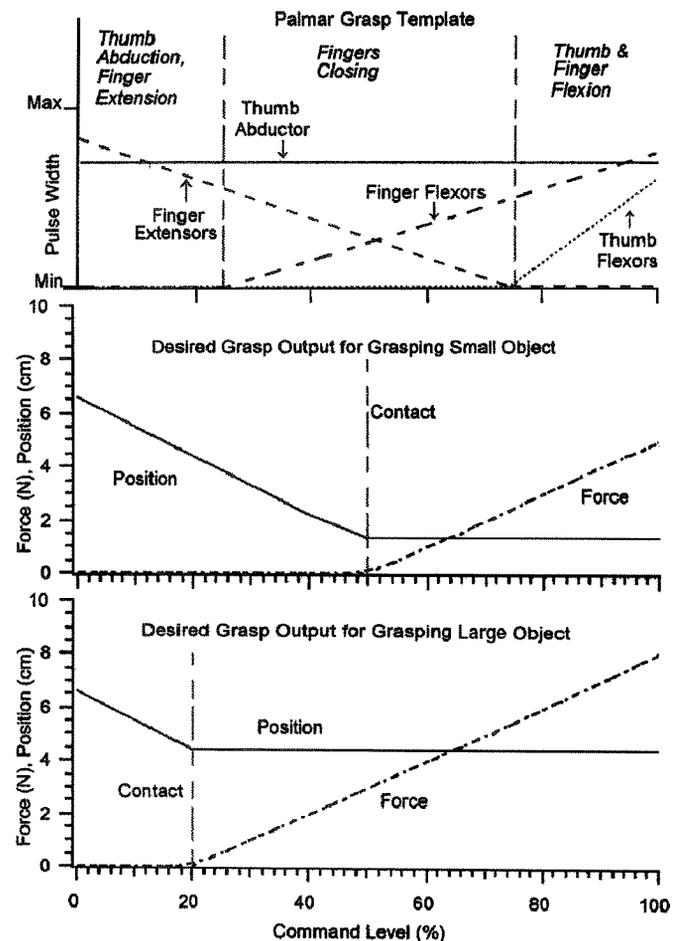


Figure 5a. Ideal templates (left) and actual stimulus patterns and input-output properties (right) for palmar grasp. Stimulus patterns are shown at the top, and input-output properties are shown at the middle and bottom for small and large objects (spacers) respectively. The nonlinearity measures of the force and opening input-output curves were 0.4 and 2.1 respectively for the small spacer, and 0.96 and 3.38 for the large spacer.

Figure 5b shows the palmar grasp stimulation pattern utilized by subject D, with the corresponding measured input/output properties. The stimulation pattern differed from the template in several ways. Thumb extensor stimulation was included to provide a wider grasp opening than thumb abduction alone. Thumb abductor stimulation was increased throughout the command range instead of maintaining a constant level so that the thumb would remain in opposition to the fingers as finger force increased. Thumb flexor stimulation started at 50 percent instead of 75 percent command to allow thumb force to be controlled over a wider command range. This stimulation pattern produced input/output curves that differed from the desired curves more than they did for the lateral grasp examples. This difference was not consistent across subjects, since the modification

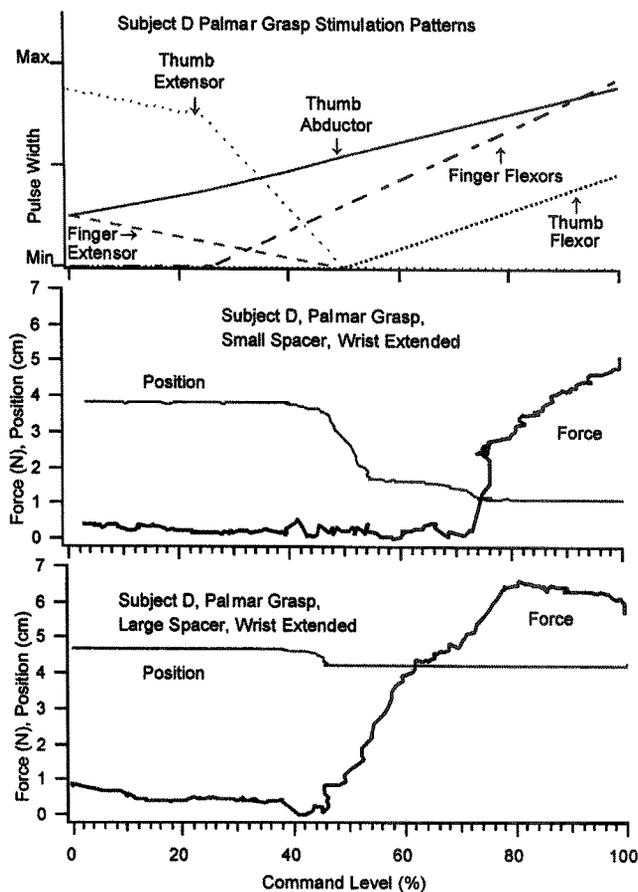


Figure 5b. Actual stimulus patterns and input-output properties (right) for palmar grasp.

of the template patterns depended more on individualized factors, such as electrode placement, muscle denervation and muscle strength.

A deadband covered the initial 40 percent of command for both the small and large spacers. This was probably due to two factors: thumb abduction often changes the orientation of the thumb into opposition without altering the grasp opening; and relaxing the finger extensor muscles with the wrist in an extended position may not result in much movement: stimulation of the antagonist flexor muscles may be required to overcome the stiffness. In the small spacer example, there were also high gain regions where opening or force changed quickly over a small command range. For example, opening changed from about 4 cm to 2 cm over an 8 percent command range (46–54 percent command), and force changed from 0 to about 3 Newtons over a 4 percent range (72–76 percent command). As expected, contact occurred sooner with the large spacer than with the small spacer, so force began to increase earlier

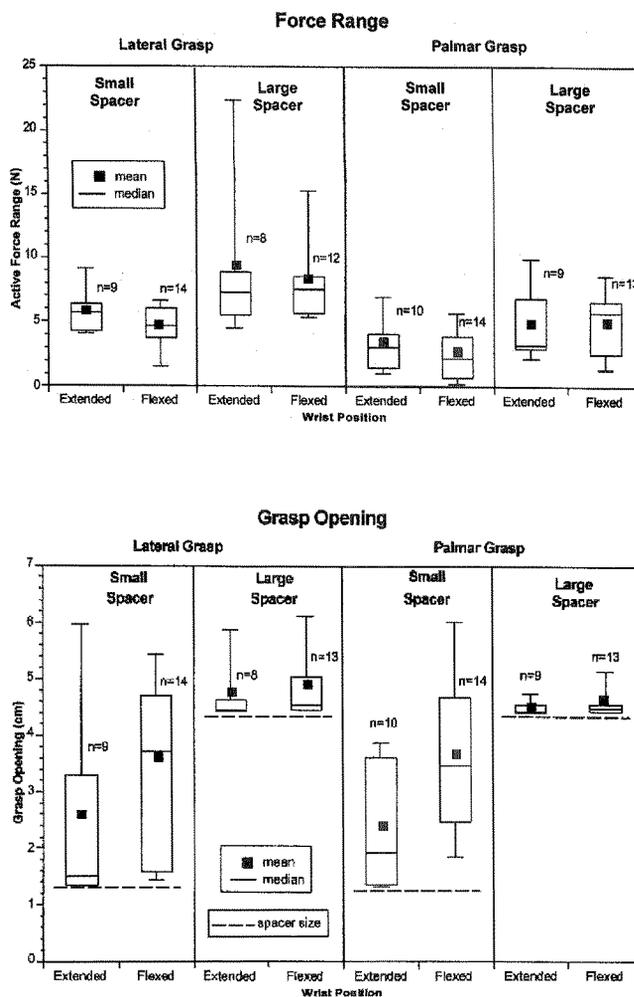


Figure 6. Active grasp force and grasp opening ranges as a function of grasp mode, spacer size, and wrist position. Data are presented as box plots, where the square symbol gives the mean, the horizontal line gives the median, the vertical limits of the box give the middle quartiles, and the upper and lower limits of the vertical line give the 90th and 10th percentiles, respectively. In the grasp opening plots, the smallest grasp opening is limited by the spacer size, indicated by the horizontal dashed lines. The numbers for each box plot refer to the number of subjects included in the graph. Of the 14 subjects, 4 did not have voluntary wrist extension, 1 did not perform trials with the large spacer, and 3 subjects had a trial where some of the data were unusable.

and reached a higher magnitude. With the large spacer, we believe that the slight decrease in force over the last 20 percent of command range was due to the finger flexors flexing the wrist, which reduced the grasp force contributed by tenodesis.

The force and grasp opening ranges for all the subjects for the initial clinic visits are summarized in **Figure 6**.

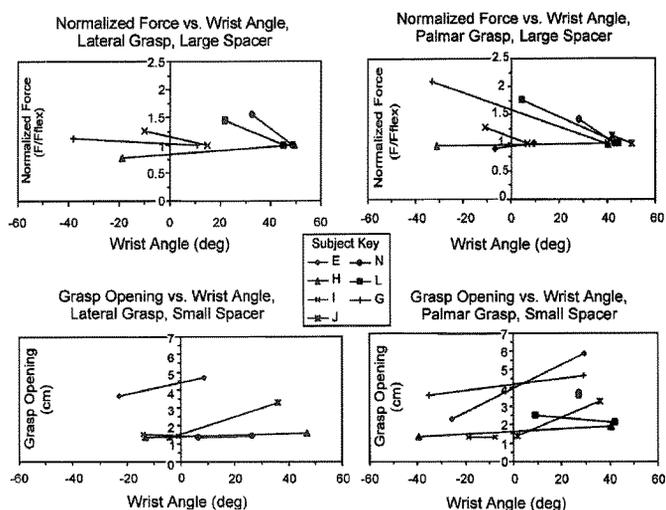


Figure 7.

Grasp opening and force measurements for individual subjects at two different wrist positions for each of the grasp modes. Wrist position was measured for seven of the neuroprosthesis users. On the horizontal axis, wrist flexion is positive and wrist extension is negative. The force values are normalized to the force measured at the wrist-flexed position. The force data for the large spacer is presented along with the grasp opening data for the small spacer.

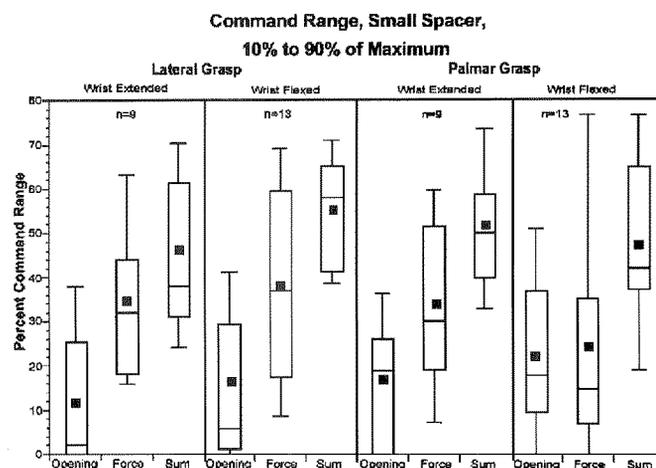


Figure 8b.

Portion of the command ranges covering 10% to 90% of the grasp opening and force ranges for the small spacer as a function of grasp mode and wrist position. The sum of the grasp opening and force command range portions is also shown, indicating the portion of the command range during which most of the grasp output changes occur. The numbers for each box plot refer to the number of subjects included in the graph. Of the 14 subjects, 4 did not have voluntary wrist extension and 1 did not have command recorded.

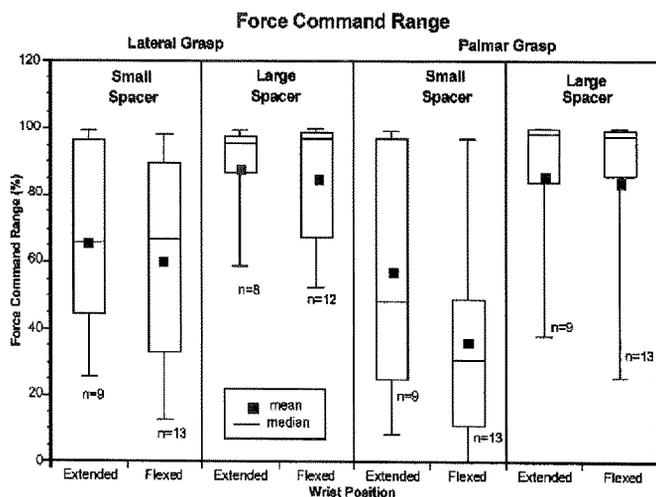


Figure 8a.

Command ranges for force control as a function of grasp mode, spacer size, and wrist angle for the initial clinic visits. Data are presented in Box Plot format (see legend of **Figure 6**). Since the entire command range is divided into either force or position control, the percentage of the range for position control is 100% minus the range for force control. The numbers for each box plot refer to the number of subjects included in the graph. Of the 14 subjects, 4 did not have voluntary wrist extension, 1 did not have command recorded, and 2 had a trial where some of the data were unusable.

Passive grasp forces were subtracted from the total force for all trials so that changes in force due to the stimulation could be studied. The forces obtained with the large spacer (mean 6.9 N) were significantly higher ($p < 0.05$, ANOVA) than those obtained with the small spacer (mean 4.1 N). In addition, force was significantly higher in lateral grasp (mean 6.8 N) than in palmar grasp (mean 4.1 N). The mean maximal grasp opening for each spacer size with the wrist flexed was similar for both grasp modes (approximately 3.6 cm for the small spacer and 4.8 cm for the large spacer). Ten subjects also performed the input/output tests with the wrist extended. Wrist extension increased mean force by 0.6 N and decreased mean opening by 0.7 cm. The effect of wrist position was statistically significant for grasp opening but not for force.

The changes in grasp force and grasp opening with wrist angle shown in **Figure 7** for individual subjects illustrates the wide variation of both flexed and extended wrist angles at the extremes of command range (maximal grasp force and maximal grasp opening), as well as the individual changes in force and opening with wrist angle. Thus, in some subjects the differences in maximal force could be as high as a factor of 1.5 or 2, even though the difference across the whole subject pool was not significant statistically.

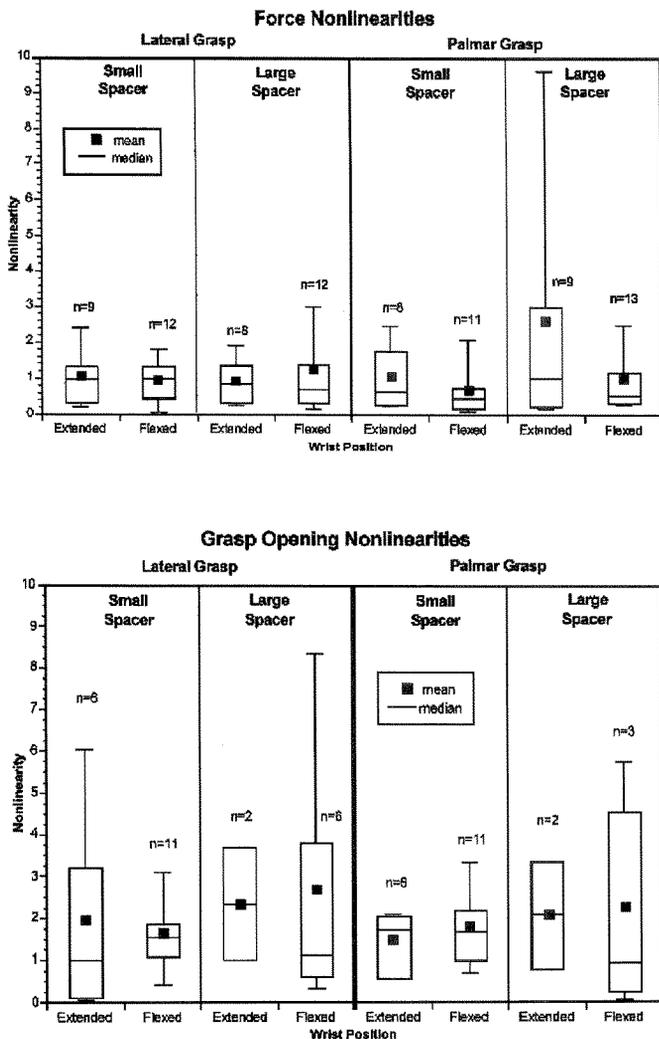


Figure 9.

Nonlinearity measures of force-command and opening-command curves for both grasp modes, both spacers, and both wrist positions. Data are presented in Box Plot format (see legend of **Figure 6**). The numbers for each box plot refer to the number of subjects included in the graph. Of the 14 subjects, 4 did not have voluntary wrist extension, 1 did not have command recorded, 3 had a trial where some of the data were unusable, and grasp opening nonlinearities were not calculated in several trials if there was no change in the grasp opening.

As **Figures 4** and **5** illustrate for one subject, object size affects how the command range is balanced between force and position control. Across the whole subject population, the average percentage of the command range that contributed to force production (**Figure 8a**) significantly increased with spacer size (53 percent command for the small spacer, 85 percent command for the large spacer), but did not depend significantly on grasp mode or wrist position (ANOVA, $p < 0.05$). With the large

spacer, the fingers contacted the object at a lower command level, thus increasing the percentage of the command range available for force production.

In the above analysis, the entire command range was divided into two segments (force control and position control). Since the input-output curves often have a sigmoidal shape, the portion of the command range that contained from 10 to 90 percent of the grasp opening changes and from 10 to 90 percent of the force changes was also quantified to summarize the command range over which most of the grasp output changes occur. **Figure 8b** displays the 10–90 percent command ranges for grasp opening and force (and the sum of the two) for both grasp modes and wrist positions using the small spacer. The sum of the command ranges for each case was approximately 50 percent, indicating that little change occurs in the grasp output for half of the command range when grasping small objects. These command range measurements did not depend significantly on grasp mode or wrist position (ANOVA, $p < 0.05$).

Figure 9 summarizes the nonlinearity measures for the input-output curves for the initial clinic visits. The force-command curves were significantly more linear (paired *t*-test, $p < 0.05$) than the opening-command curves (mean nonlinearity value of 1.2 vs. 1.9). This is also true of the specific examples shown in **Figures 4** and **5**. There was no significant effect of wrist position, spacer size, or grasp mode on the nonlinearity (ANOVA, $p < 0.05$).

The average grasp opening and force measurements across the three clinic visits are summarized in **Figure 10**. The data show both grasp modes and spacer sizes with the wrist in the flexed position. The grasp force did not vary significantly with time, but grasp opening for the small spacer did show a decrease of 36 percent that was significant statistically (repeated measures ANOVA, $p < 0.05$).

DISCUSSION

Previous reports of neuroprosthetic hand grasp output have focused on the maximum grasp force (10–12) or have included sample grasp data from one or two neuroprosthesis users (3,7). This study examined grasp force and opening control throughout the command input range, and includes a large enough user population to allow a statistical analysis of grasp outputs across patients.

The observation that grasping a large object produced a larger force than grasping a small object was not surprising, since it has been shown previously in unimpaired persons (13) and in individual neuroprosthesis users (3,7),

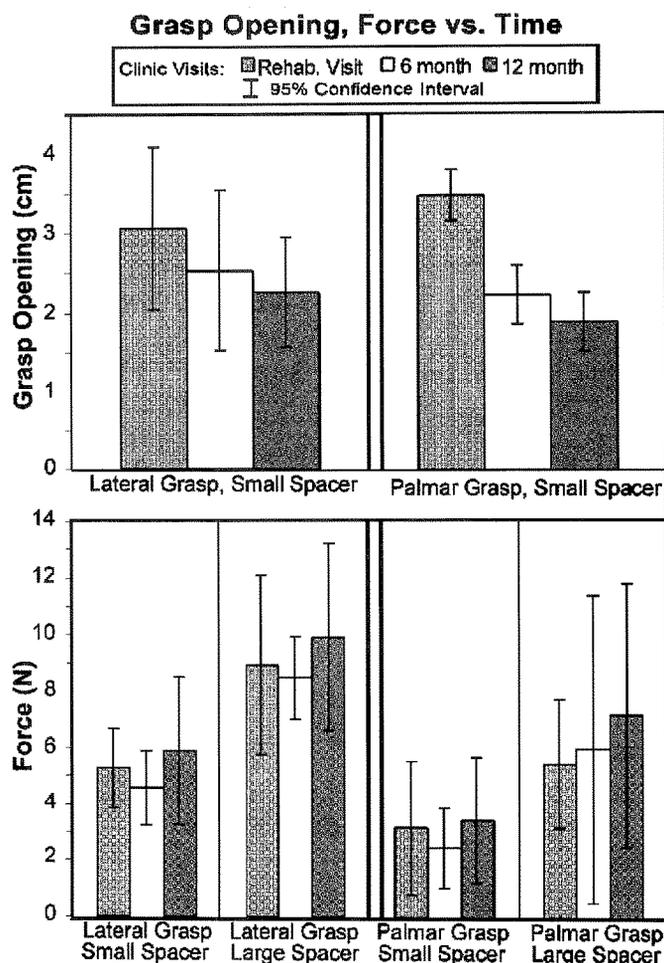


Figure 10.

Mean grasp opening and force values for eight subjects who performed the input/output properties tests at their post-implant rehabilitation visit, and at follow-up visits at approximately 6 mo and 1 yr later. The trials included in this data are for the wrist in the flexed position. Grasp opening values with the large spacer are omitted since the spacer limits the minimal opening. The error bars are the 95% confidence limits.

but it had not previously been shown to be a significant effect across a large number of neuroprosthesis users. This effect is presumably due to the length-tension properties of muscle (14). The fingers are more extended when grasping a larger object, so the flexor muscles are lengthened and are able to produce a larger force.

Similarly, the finding that the percentage of the command range that was used for force production increased with spacer size was not surprising. However, since the wrist position and grasp mode both affect the initial grasp opening and could affect the shape of the input-output curve, the effect of wrist position and grasp mode were not previously known.

The fact that lateral grasp forces were greater than the palmar grasp forces was probably due to the different muscle groups that were utilized for each grasp. In palmar grasp, force is generated mainly by the finger flexor muscles, which if stimulated at too high a level will also produce a wrist flexion moment; that would be undesirable for a functional grasp. Therefore, finger flexor stimulation was programmed at a level below the maximum force-generating capacity. In lateral grasp, force is generated mainly by the Adductor Pollicis, an intrinsic thumb muscle that has no wrist moment component, since it does not cross the wrist. Higher force measurements for lateral grasp have also been reported by others (10–12).

The lack of a significant effect of wrist position on maximal active grasp force was unexpected, since others have shown grasp force to vary with wrist position in unimpaired subjects (15,16), and since the tenodesis effect provides some grasp capability even without active flexors. One reason for the weak effect observed in this study may be that our measurements subtracted out initial passive forces. In addition, there was a wide variation in the angles tested (Figure 7), since the users voluntarily selected their wrist position (as opposed to being set by the experimenter), and because the wrist extensors are weakened and wrist flexors paralyzed in these neuroprosthesis users. The significant effect of wrist position on grasp opening does not contradict the small effect on active force, since the position range is dominated by passive forces opposing the stimulated muscles.

The indication that most of the grasp output changes occur in 50 percent of the command range (Figure 9b) demonstrates that the desired grasp output portrayed in Figures 4 and 5 has not been achieved. This deviation from the ideal grasp output is a result of the nonlinearities in both the grasp opening and force curves.

System nonlinearities, such as deadbands and high gain regions, have been shown to increase isometric force tracking errors both in simulations and in neuroprosthetic hand grasp (9). The average static force nonlinearity (1.2) in the present study is comparable to that reported for the two subjects in the tracking study (0.5 to 1.4), and reduction of the nonlinearity in that study increased tracking performance. The nonlinearity of position control has not been reported previously, but in the current study it is substantially larger than the force nonlinearity. Thus, improved performance under conditions similar to tracking might be expected if static nonlinearity was reduced for all subjects. Since tracking studies involve dynamically modulating the output, they are analogous to real-life conditions where the subject has to accurately adjust grasp

output during manipulation. Techniques to reduce nonlinearity include closed loop control (17) or detailed inverse mapping of the input properties (18). These techniques have been tested in experiments with subjects, but have not been incorporated into clinical practice.

Currently in the clinical implementation, the nonlinearities are reduced through an iterative grasp programming method, starting with the grasp templates shown in **Figures 4** and **5**, and then modifying the grasp pattern to optimize the grasp, as assessed qualitatively by the clinician. The modifications can include altering the stimulus duration or amplitude for an electrode, adding agonist or antagonist muscles, or shifting the location in the command range where the electrodes are activated. This is inherently a noninstrumented inverse mapping technique that is based on only five points along the command axis, assumes that the nonlinearity is repeatable, and assumes it depends only on command. However, since we have shown in this study (**Figures 4** and **5**) and elsewhere (3) that the nonlinearities can be affected by object size, wrist position, and muscle fatigue, it is impossible to eliminate the nonlinearities completely by a simple inverse mapping. Closed-loop control is not yet practical, since the required force and position sensors are unavailable in a wearable format that is acceptable to the system users.

We believe that the measured grasp opening nonlinearities were greater than the force nonlinearities for a number of reasons. First, only a small number of points along the command axis are used to adjust the stimulation levels for position control. Pulse widths are linearly modulated between these endpoints. The same is true for force modulation. However, the relationship between stimulation and position is inherently less linear than for force control. Without cocontraction of antagonists, joint positions are achieved by balancing the active and passive joint moments. Since the relationship between passive joint moment and joint angle is sigmoidal, only a small change in moment is required to move from one end of the range of movement to the other, while large changes in moment at either extreme produce little further movement (19). Thus, even if the stimulation modulates muscle force linearly, the resulting change in joint angle will be nonlinear. In addition, the distribution of optimal muscle fiber lengths is non-uniform (20).

The reasons for the observed decrease in grasp opening across the three clinic visits are uncertain and warrant further investigation. Six of the eight neuroprosthesis users who completed all three visits had modifications made to their grasp patterns during the second or third visit (or during additional visits that occurred within the period

covered in this study). These grasp modifications were mainly due to three factors: 1) altered muscle strength that adversely affected the grasp (e.g., increased finger flexor force causing unwanted wrist flexion); 2) inadvertent stimulation of adjacent muscles (spillover) that appeared to increase over time in a few of the users; and 3) individual preference (a user wanting more or less force for a particular task). The grasp modifications may have contributed to the reduction in grasp opening, but there was not a clear correlation.

Two other possible explanations for the decreased grasp opening over time are exercise-related. If the stimulated exercise pattern causes the flexor muscles to increase in strength more than the extensor muscles, the hand may assume a more flexed posture over time. In addition, if a neuroprosthesis user discontinues stretching and range-of-motion exercises, an increase in passive stiffness may occur over time. There was not enough information in the population of users in this study to evaluate these two potential causes of decreased grasp opening, but they warrant further investigation as the population of neuroprosthetic hand grasp users increases.

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