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Identification of key pinch forces required to complete functional tasks

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Abstract—Reconstructive hand surgeries restore key pinch to individuals with pinch force deficits caused by tetraplegia. Data that define the magnitudes of force necessary to complete functional key pinch tasks are limited. This study aims to establish target pinch forces for completing selected tasks that represent a range of useful functional activities. A robot arm instrumented with a force sensor completed the tasks and simultaneously measured the forces applied to the task objects. Lateral pinch force requirements were calculated from these measured object forces. Pinch force requirements ranged from 1.4 N to push a button on a remote to 31.4 N to insert a plug into an outlet. Of the tasks studied, 9 of 12 required less than 10.5 N. These pinch force requirements, when compared to pinch forces produced by 14 individuals with spinal cord injuries (with and without surgical reconstruction of pinch), accurately predicted success or failure in 81% of subject trials. The prediction errors indicate a need to measure other factors such as pinch opening, force location, force direction, and proximal joint control.

INTRODUCTION

Reconstructive hand surgeries can restore grasp and pinch function to individuals following cervical spinal cord injuries (SCIs). Tendon transfer, tenodesis, and joint stabilization procedures are strategically planned based on the muscles remaining under voluntary control and provide stability and restore strength to the upper limbs [1–3]. Typically, surgeons restore lateral pinch (often referred to as key pinch) because of its versatility in hand function and the probable availability of donor muscles [4]. The main objective of these surgical reconstructions is to improve pinch force between the pad of the thumb and the lateral aspect of the index finger, with the expectation that the individual's ability to perform activities of daily living (ADLs) will improve accordingly. However, data that define the target force magnitudes necessary for a significant change in functional outcome are limited.

Clinicians use various measures to evaluate the efficacy of surgical procedures that restore hand function. Measurements of pinch force magnitude (recorded using a clinical pinch meter) [5–9], patient satisfaction surveys and questionnaires [5,6,10,11], and clinical dexterity tests, such as the Jebsen and Sollerman tests [12–14], provide

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Abbreviations: ADL = activity of daily living, ATM = automated teller machine, SCI = spinal cord injury, SD = standard deviation, VA = Department of Veterans Affairs, VAPAHCS = VA Palo Alto Health Care System.

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evidence for evaluating the effectiveness of a particular surgical procedure. Quite often, patients have little or no measurable pinch force preoperatively, so any increase in pinch force postoperatively is expected to result in improved functional performance. However, the relationship between increase in pinch force and functional improvement needs to be defined more conclusively [15]. By defining the pinch force needed to accomplish selected ADLs, we can improve predictions of functional outcome following tendon transfer surgeries and identify the patients who would benefit most from surgery.

This study establishes the target pinch force requirements necessary to accomplish simple ADL tasks requiring lateral (or "key") pinch. Once identified, these target pinch force magnitudes can be used as a quantitative measure of surgical outcome with functional significance. Pinch force magnitude and the ability to perform the tasks are recorded in 14 individuals with SCI, resulting in pinch force deficits. The results of this study define pinch force requirements that have the power to predict, with great confidence, whether an individual has sufficient pinch force magnitude to complete each task.

METHODS

Task Analysis: Defining Target Pinch Forces

The tasks chosen represent a range of pinch force magnitudes and require the ability to assume a variety of proximal joint positions, hand postures, and pinch openings.

The ADL tasks used in this study are—

- Opening and closing two types of zippers (one to represent a smaller "clothing" zipper—oriented vertically at the chest—and another to represent a larger "backpack or book bag" zipper—oriented horizontally on the lap).
- Inserting and removing a plug.
- Inserting and removing a key.
- Inserting and removing an ATM (automated teller machine) card.
- Stabbing "food" with a fork.
- Using a remote control button.

The majority of the tasks include items requiring lateral pinch from the Sollerman hand function test in tetraplegia (inserting key into lock, opening and closing zipper, and using a fork) [13]. Other tasks (ATM, remote) were identified based on the recommendation of the occupational therapist/SCI clinical specialist who is the hand-clinic coordinator for SCI in the Department of Veterans Affairs (VA) Palo Alto Health Care System (VAPAHCS), with extensive clinical experience in SCI rehabilitation pre- and posttendon transfer surgery.*

The plug task was added to include a task that required a wider pinch opening. Because we were using pinch force magnitude (isometric strength) as an outcome measure, tasks that required manipulation (dynamic control) were not included, such as picking up objects or buttoning clothes. The five tasks with two phases (opening-closing or inserting-removing) were evaluated separately, for a total of 12 tasks.

Each object was fixed to the end of a robotic arm programmed to move in a direction for a distance to complete the corresponding task. After the object was fixed to the robot, the force sensor was biased and the force applied to the object was measured, simultaneously with task performance, with the use of a force sensor mounted on the "wrist" of the arm (**Figure 1(a)**). We collected these data at 100 Hz using a LabVIEW Data Acquisition (DAQ) interface (National Instruments, Austin, Texas, USA), a PUMA 260 Industrial Robot (Staübli Corp., Duncan, South Carolina, USA) and an ATI Mini-40 6-axis force sensor (ATI Industrial Automation, Apex, North Carolina, USA). The peak force applied to the object (*object force*) was identified for each trial (see typical force trace, **Figure 1(b)**). The robotic arm performed each task a total of nine times: three trials of each task at three speeds. We chose slow speeds to minimize possible effects from viscous friction (viscous friction effects could cause an increase in force with an increase in speed). **Table 1** is a description of the task specifications and the time the robotic arm took to complete each task.

Data Analysis

Differences in peak force magnitude across the three different speeds were evaluated by Friedman's nonparametric tests for each task, and any significant differences were tested with the Wilcoxon signed rank test for pairwise comparisons at the $p < 0.01$ significance level. No significant differences were found in peak force magnitude because of the three selected speeds of the task performance. The mean of the peak forces for the nine trials plus 2 standard deviations (SDs) was defined as the required force that must be applied to the object (*object force requirement*) for the task to be completed. This

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*Personal communication, J. Weiss, March 1998.

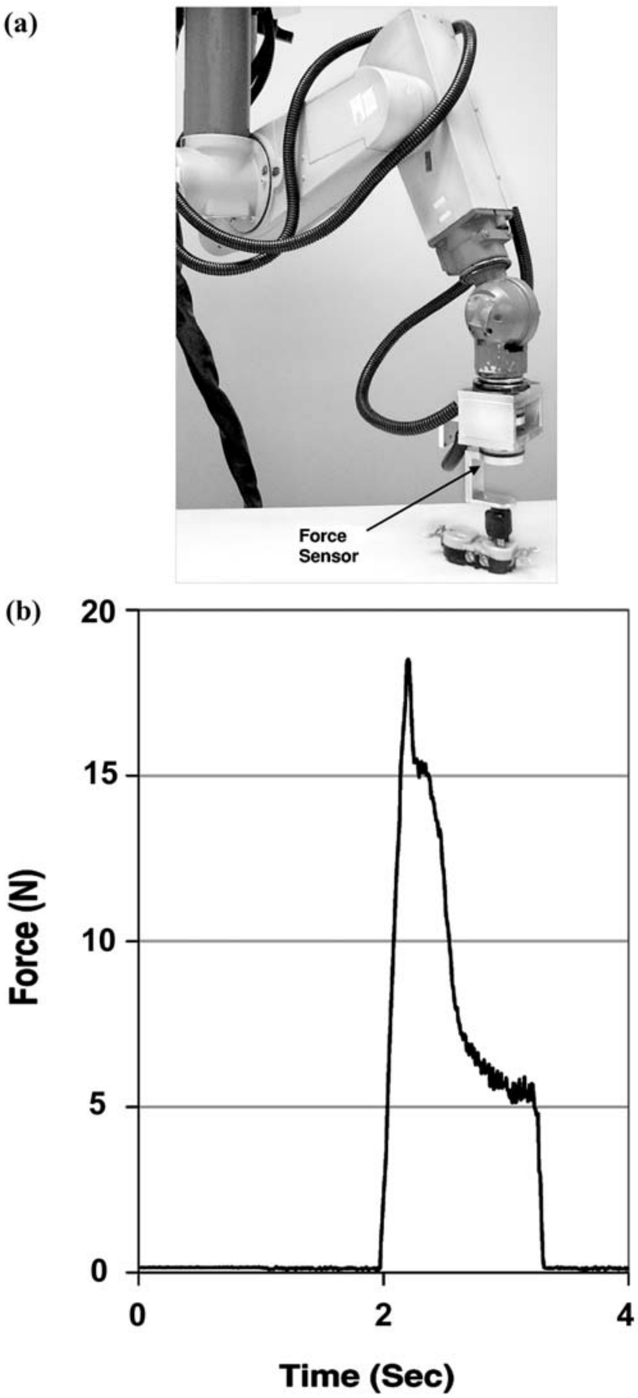

Figure 1.
(a) Typical experimental setup of force sensor mounted to robotic arm to perform a task. A plate mounted to the force sensor contacts object (plug), and robotic arm is programmed to push it a specific distance into receptacle. **(b)** Plot of force imparted to object as a function of time (for plug in task). Peak force magnitude is recorded, and time to complete task is calculated from onset and cessation of force.

definition increased the chances (to 95%) that the actual requirements for the object force would be at or below this value, covering variance in experimental or environmental conditions. In only 2 of 108 experimental cases was the object force greater than the mean plus 2 SDs measured. In one case, the amount greater was 0.004 N (well within the accuracy of our sensor), and in the other case (closing of large horizontal zipper), the value was 0.44 N (3.6%) greater, for a calculated value of 12.15 N (this was caused by one outlying measurement that could not be discounted as error).

When humans perform the ADL tasks chosen, they grasp the objects with key pinch and apply force to the object to move it in a direction necessary to complete the task (e.g., inserting a key). The forces that are applied to the object are transmitted through the frictional interface between the object and the thumb and index finger. Therefore, once the object force requirement for each task is defined, a corresponding range of key pinch force (*pinch force range*) is calculated with coefficients of friction ($0.33 < \mu < 0.56$) consistent with the interaction between dry skin (tetraplegic individuals often have dry skin) and the materials of the chosen objects [16].

Figure 2 illustrates the relationship between the key pinch force and the object force. Less slippery interactions (μ greater) fall in the lower end of the pinch force range, while more slippery interactions (μ lesser) require a greater pinch force. This analysis was not required for the “remote” task, because the object force (the button push) and the key pinch force are identical.

Subject Testing

Fourteen subjects (one patient was tested bilaterally for a total of 15 hands tested) with SCI were recruited from the Hand and Upper Extremity Clinic of the VAPAHCS. All subjects provided informed consent. The subjects included five patients who were scheduled for reconstructive hand surgery (preoperative group), five patients who had previous tendon transfer surgery to restore key pinch (postoperative group), and four patients who had residual pinch function and did not have tendon transfer to flexor pollicis longus surgery (nontransfer group). The subjects in the postoperative group had C5–7 level injuries; two were incomplete (four males, one female, ages 38 to 66 years). The postoperative group had C4–7 level complete injuries (five males, ages 44 to 59 years, 8 to 18 years postoperative). This group had three transfers of brachioradialis to flexor pollicis longus

Table 1.
ADL task descriptions (as measured).

Task	Description	Pinch Opening (mm)	Mean (SD)			
			Time (s) N = 9	Time 1 (s) N = 3	Time 2 (s) N = 3	Time 3 (s) N = 3
Fork In	4-tine fork, into Air Putty, medium, soft	2.0	2.0 (0.4)	2.3 (0.2)	2.3 (0.2)	1.5 (0.1)
Key In	Standard key into an entrance lock	2.4	1.7 (0.8)	2.6 (0.7)	1.7 (0.01)	0.8 (0.01)
Key Out			1.9 (0.7)	2.6 (0.06)	2.1 (0.03)	1.1 (0.04)
Plug In	3 prong plug, into wall outlet	22.9	1.5 (0.4)	1.6 (0.5)	1.3 (0.2)	0.9 (0.3)
Plug Out			1.1 (0.5)	1.6 (0.2)	1.1 (0.1)	0.6 (0.1)
Vertical Zipper						
Closed	5 mm closure width, 2 cm zipper tab	1.6	11.4 (4.1)	15.7 (0.04)	12.4 (0.04)	6.2 (0.2)
Open			15.6 (6.3)	22.4 (1.5)	16.3 (0.4)	7.3 (1.5)
Horizontal Zipper						
Closed	8 mm closure width, 1.5 cm zipper tab	1.8	8.6 (3.0)	13.8 (0.9)	9.2 (0.8)	4.5 (0.4)
Open			9.2 (4.0)	11.5 (1.2)	9.5 (0.1)	4.7 (0.1)
ATM						
In	Standard card into (actual) ATM mechanical device	0.7	3.8 (1.6)	5.5 (0.3)	3.7 (0.04)	2.3 (0.1)
Out			3.0 (1.7)	4.8 (0.1)	2.9 (0.1)	1.4 (0.1)
Remote Button Pressed	Doorbell remote, button diameter 13.6 mm	22.0	0.9 (0.2)	1.1 (0.1)	0.9 (0.03)	0.7 (0.1)

and three transfers of pronator teres to flexor pollicis longus (in one subject with dual transfers, right and left sides were tested). In the nontransfer group (four males, ages 35 to 67 years), three subjects had incomplete injuries (C5–6) and one had a complete injury (C5–8) with procedures to restore grip (i.e., finger function), but none had active transfer to flexor pollicis longus.

We recorded measurements of pinch force magnitude using a clinical pinch meter (Greenleaf Medical Systems, Palo Alto, California). The pinch meter was placed on the lateral aspect of the subjects' index fingers as the subjects pressed down on the force button with the thumb. The subjects assumed a comfortable posture, resting forearms on a table in front of them. The pinch meter required a pinch opening of 21 mm. The resolution (or measurement increment) of the pinch force measurements was 0.445 N. We defined each subject's *pinch force measurement* as the mean of three trials to account for possible variations in the location of thumb contact with the force button, which could affect the force reading. The subjects were then evaluated on their ability to complete the same

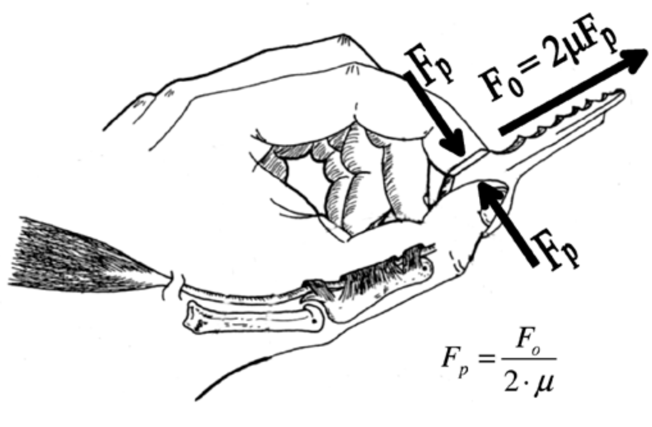

Figure 2.
Lateral pinch force requirement was calculated from object forces measured by robot-mounted force sensor. Analysis assumed all force imparted to object was via friction between object and index finger and thumb. F_p refers to the lateral pinch force or the "pinch force requirement." F_o refers to force measured by robot or "object force requirement." μ is coefficient of friction between object and skin. (Illustration adapted from Clinical Mechanics of the Hand, P. Brand and A. Hollister, 1999.)

tasks that the robot performed. If the subjects attempted to use adaptive strategies such that the interaction with the objects were not pure key pinch, the subjects were asked to perform the tasks again without these strategies.

We used a comparison of each task's pinch force requirement to each subject's pinch force measurement to predict the subject's task performance. The maximum magnitude in the task's pinch force range was defined as the *pinch force requirement* value for each task (i.e., we assumed the most slippery condition). If the subject's pinch force measurement was greater than the task's pinch force requirement and the subject performed the task successfully or if the subject's pinch force measurement was less than the task's pinch force requirement and the subject could not perform the task, the trial was predicted correctly. Two types of error outcomes were possible:

1. Incorrect prediction of failure (Type I error): The subject's pinch force measurement was insufficient, but the subject could perform the task successfully.
2. Incorrect prediction of success (Type II error): The subject's pinch force measurement was sufficient, but the subject was unable to perform the task.

Using the maximum of the pinch force range resulted in a conservative estimate for the pinch force requirement (in addition, the range was calculated from an object force requirement equal to the mean plus 2 SDs). This was a conscious choice in an attempt to effectively eliminate incorrect predictions of success (Type II errors) caused by underestimated task pinch force requirements. The advantage to this strategy is that it produces conservative goals for clinicians; i.e., if a patient's pinch force measurement exceeds the task's pinch force requirement, the clinician can state with great confidence that the pinch force magnitude is sufficient to complete the task. Or, when viewed another way, if a subject is unable to complete the task with sufficient pinch force magnitude, the clinician can attribute the failure to other factors (such as reduction in force with pinch opening, pinch force direction errors, proximal joint limitations, etc.). A disadvantage of this strategy is that it will inherently produce more incorrect predictions of failure (Type I errors).

RESULTS

The selected tasks represent a range of pinch force requirements (**Figure 3**). The pinch force requirements for the tasks span from 1.4 N (push remote button) to

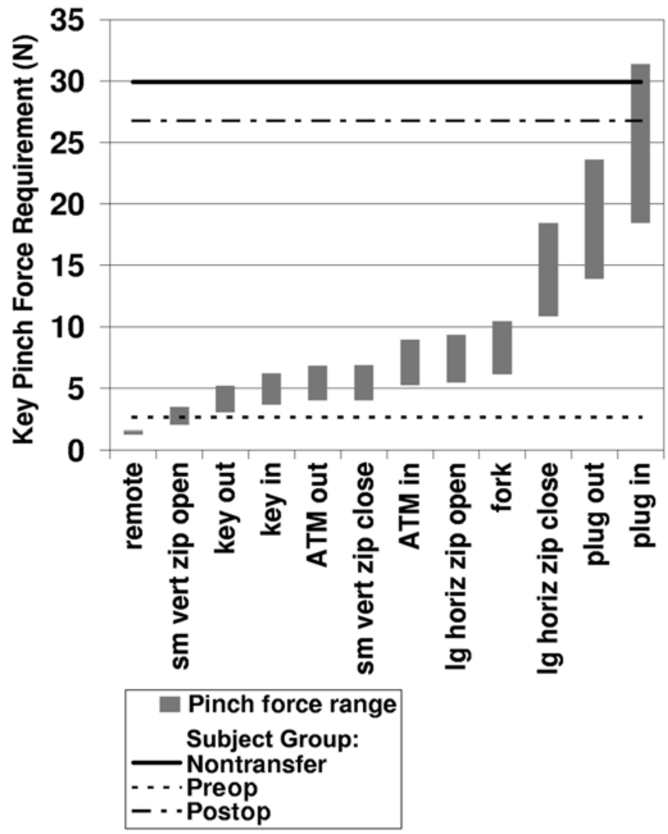

Figure 3.
Pinch force (N) requirement range for each of ADL tasks. Range of pinch force requirements is due to possible variability in coefficient of friction between objects and thumb and index finger. Mean pinch force magnitude for each of subject groups described in text is indicated.

31.4 N (insert plug—under the most slippery condition, $\mu = 0.33$, top of the force range bars on **Figure 3**).*

All the tasks except inserting and removing the plug and closing the large horizontal zipper require a maximum pinch force of 10.4 N or less (9/12 tasks). The minimum value of the range indicates the pinch force required when the pinch conditions are less slippery ($\mu = 0.56$).

The mean pinch force measurement by subject group is also indicated in **Figure 3**. The preoperative group had a mean of 2.6 N (range 0.5 N to 8.0 N), the postoperative group 26.8 N (range 16.0 N to 38.9 N) and the nontransfer group 29.9 N (range 13.8 N to 49.9 N). In this study, three of the four nontransfer group subjects sustained incomplete injuries, explaining their higher residual or

*Conversion factor: 1 N – 0.225 lb

recovered mean pinch force magnitudes versus the postoperative group. These plotted lines in **Figure 3** are included only to indicate the general relationship between the groups' pinch force measurements and the task pinch force requirements, and were not used to predict task performance.

We predicted task performance by comparing the individual subject's pinch force measurements to each task's pinch force requirements. Of the 180 tasks performed (15 hands performed 12 tasks), 146 (81.1%) were predicted correctly by this criterion. Task trials in which subjects had sufficient pinch force (113 trials) and successfully completed the task accounted for 93 of the "correct" predictions. The remaining 53 correct predictions were from trials in which subjects had insufficient pinch force (67 trials) and failed to complete the task. Incorrect prediction of failure, in which the subject had insufficient pinch force but performed the task successfully, accounted for 14 errors (20.9% of cases with insufficient pinch force, Type I error). Incorrect prediction of success, in which the subject had sufficient pinch force but failed to complete the task, accounted for 20 errors (17.7% of cases with sufficient pinch force, Type II error). The overall prediction results are shown in **Table 2** and are broken down by task and subject group in **Table 3**.

A sensitivity analysis of the prediction errors versus changes to our pinch force requirements is shown in **Figure 4**. This graph shows that our rate of incorrect predictions of failure (Type I errors) decreases with reductions in task pinch force requirements. However, it also shows that a decrease of 25 percent (or greater) in the task pinch force requirements will slightly increase the rate of incorrect predictions of success (Type II errors).

Table 2.
Predictive success of subject task performance. Gray shading indicates correct predictions.

		Actual Task Performance		Total
		Success	**Failure**	
Predicted Result	**Success**	93 (82.3%)	20 (Type II)	113
	Failure	14 (Type I)	53 (79.1%)	67

Table 3.
Predictive success separated by subject group and task.

Task Performance	Prediction	Group	Narrow Grasp Opening (N)									Wide Grasp Opening (N)		
			ATO 4.0–6.8	**ATI** 5.3–8.9	**KeyO** 3.0–5.0	**KeyI** 3.7–6.2	**Fork** 6.1–10.4	**VZpC** 4.0–6.9	**VzpO** 2.0–3.5	**HZpC** 10.9–18.4	**HzpO** 5.5–9.3	**Rem** 1.4	**PlugI** 18.5–31.4	**PlugO** 13.9–23.6
Success Pinch F > Task F	Correct	Pre	—	—	—	—	—	—	1	—	—	1	—	—
		Post	5	4	4	5	6	5	6	3	5	6	2	3
		Non	3	3	3	3	4	4	4	2	3	4	2	2
Failed Pinch F < Task F	Correct	Pre	4	5	4	4	3	4	4	5	5	3	5	5
		Post	—	—	—	—	—	—	—	—	—	—	—	—
		Non	—	—	—	—	—	—	—	1	—	—	1	—
Success Pinch F < Task F	Incorrect (Type I)	Pre	—	—	—	—	2	—	—	—	—	—	—	—
		Post	—	—	—	—	—	—	—	2	—	—	4	3
		Non	—	—	—	—	—	—	—	—	—	—	1	2
Failed Pinch F > Task F	Incorrect (Type II)	Pre	1	—	1	1	—	1	—	—	—	1	—	—
		Post	1	2	2	1	—	1	—	1	1	—	—	—
		Non	1	1	1	1	—	—	—	1	1	—	—	—

Note: Numbers indicate subjects in each prediction category for each task. Tasks are described in **Table 1.** Range of force required to complete each task is indicated in each column heading for each task. Range of forces corresponds to height of bars in **Figure 3**. Narrow grasp opening included tasks less than 3 mm thick. Wide grasp opening included tasks at least 20 mm thick.
Pinch F = pinch force (N) recorded by pinch meter
Task F = task force (N) calculated from robot mounted force sensor
pre = preoperative group
post = postoperative group
non = nonoperated group
ATO = ATM out
ATI = ATM in
KeyO = Key out
KeyI = Key in
VZpC = vertical zipper closed
VZpO = vertical zipper open
HZipC = Horizontal zipper closed
HzipO = Horizontal zipper open
Rem = remote
PlugI = plug in
PlugO = plug out

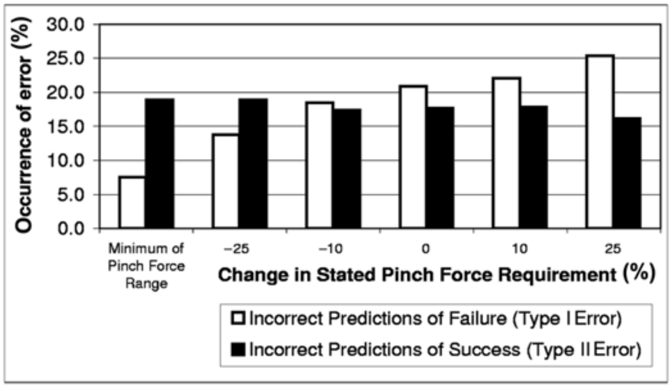

Figure 4.
Sensitivity of prediction errors to changes in defined pinch force magnitude requirements. Value of 0% on *x*-axis indicates values used in this paper to define success and failure predictions. Percentage changes –25% to +25% indicate percentage change applied to pinch force requirement for each task. First bars on graph are included to show effect of reducing pinch force requirements to μ = 0.56 value (least slippery condition, bottom of force ranges in **Figure 3**) for each task.

DISCUSSION

Target pinch force requirements were established for the selected key pinch tasks. The ability to produce 31.4 N of force in the key pinch posture was greater than or equal to the requirements for all the key pinch tasks identified in this study. The selected tasks represented a range of force requirements that were useful for assessing the pinch force deficits of individuals with SCI. In addition, successful performance of the task challenged the subjects to assume a variety of proximal joint positions and pinch openings. Knowledge of the subject's pinch force measurement enabled us to correctly predict the subject's performance in 81 percent of the cases.

We defined the required forces for each task quite conservatively by adding 2 SDs to the mean force measured by the robot and by assuming the most slippery condition in our pinch model. This conservative definition of the task pinch force requirements likely eliminates the possibility that our incorrect predictions of successful task performance (Type II errors) are due to underestimation of the task pinch force requirements. The sensitivity analysis (**Figure 4**) of our prediction errors supports this argument, because the incorrect predictions of success show little relationship to modest variations in pinch force requirements. Most likely, the force requirements are overestimated because incorrect predictions of failure (Type I errors) decrease with decreasing pinch force requirements.

From a clinical perspective, this means, if a subject is able to produce the task's pinch force magnitude requirement but is unsuccessful in performing it, the reason for failure is likely **not** pinch force magnitude. Thus, these target pinch forces are clinically relevant because, in their absence, it is easy to assume the failure to perform a task is due only to a lack of ability to produce adequate pinch force magnitude. This assumption may erroneously stimulate devising new rehabilitation and surgical strategies to increase pinch force magnitude when the impairment may be due to other factors.

We believe that our incorrect predictions of success (Type II errors) most likely have two explanations. One is a reduction in subject pinch force magnitude with reduction in pinch opening. The pinch meter used in this study measured pinch force at an opening of 21 mm, while 9 of the 12 ADL tasks required force production at pinch openings of less than 3 mm (see **Table 1**). Supporting this explanation, 19/20 (95%) of the Type II errors occurred in this task subset. One could argue that we should have selected tasks requiring wider pinch openings, but we believe instead that this highlights the importance of production of lateral pinch force at narrow openings to ADL activities and points to the need for accurate measurement of pinch force at narrower pinch openings. The other likely explanation of our Type II errors is poor positioning of the thumb or poorly directed thumb force. The pinch meter only measured magnitude of force and not the ability to direct the force or to place the thumb correctly on the lateral aspect of the index finger when pinching. One subject from each of our three groups had problems with thumb positioning, caused by either an excessive thumb interphalangeal flexion, an extended index finger posture, or a flexed and abducted thumb position. These three subjects accounted for 15/20 (75%) of the Type II errors.

In this study, we were quite careful to limit the use of adaptive strategies, because our model for converting the object force to key pinch force assumed a pure key pinch. Adaptive strategies are extremely important functionally for tetraplegic individuals, so we would expect many more incorrect predictions of failure (Type I errors) were these strategies used. Our inability to detect all adaptive strategies by our subjects may account for some of our Type I errors. For example, one common strategy that was difficult to detect was "wiggling" the plug into or out of the socket (the plug tasks accounted for 10/14 of the Type I errors).

While we make a case for using the top of the task pinch force range as the pinch force requirement, the actual frictional coefficient between an object and the skin will vary depending on the material of the object and the dryness of the skin. Dry skin can be more slippery than skin with perspiration and is often a characteristic of denervated palmar skin where sweat glands no longer function. This skin also lacks the rough rugation pattern that facilitates grip [17]. This is why, in **Figure 3**, we represent the task key pinch requirements as ranges. These findings possibly may be tailored to individual subjects and individual objects. This is complicated by many objects having some texture or irregular shapes. We did not choose to measure the effective frictional coefficients between each subject's skin and each object, deciding instead that general pinch force requirements would be more likely used in a clinic.

Looking at the data for our ADL tasks generally, by subject group, indicates that, preoperatively, individuals with C5–7 level SCIs should be unable to perform most of them with a pure key pinch (only 6.7% success rate in our subjects). Surgical procedures to restore active pinch (i.e., transfer to the flexor pollicis longus tendon) restored key pinch force magnitude to at least 16 N in our five subjects, a value greater than 9 of the 12 tasks' pinch force requirements defined here. Accordingly, the subjects in our postoperative group were able to perform most of the tasks (87.5% success rate). This level of functional performance is comparable to those individuals who did not have surgery because of sufficient residual or recovered strength (83.3% task success rate in these subjects).

CONCLUSIONS

Our hope is that these data will be used to help counsel tetraplegic individuals considering surgery, giving them a general idea of the functional independence that they might achieve postoperatively. However, when using these data, clinicians must obviously still perform individual assessments of key pinch function, because tetraplegic individuals are a very heterogeneous group. Preoperatively, there is variability in the voluntary strength, extent of denervation, and presence of hyperreflexia in the muscles selected for tendon transfer, all depending on the level and extent of injury [18]. Postoperatively, scar tissue, the ability to activate the transferred muscle [19], and proximal joint control can influence functional pinch outcome measures.

In addition to the preceding generally accepted variability in this clinical population, our data indicate that the reduction of pinch force at narrower openings has functional significance. Many everyday objects held in a key pinch posture require a narrow pinch opening, such as keys, credit cards, paper, coins, zippers, or playing cards. Our research group has begun to investigate the biomechanical factors influencing this reduction in pinch force with narrow pinch openings [20]. In addition, we hope to develop ways to measure subject's pinch force at a variety of pinch openings, although this is technically difficult to do accurately at very narrow openings.

A patient achieving a biomechanically successful key pinch posture is also quite important. Our data indicate that the ability to position the thumb and index fingers relative to each other and the ability to direct thumb force are extremely important to functional key pinch (so that the object may be held securely and does not rotate out of the hand). Our previous studies have demonstrated that because of the paralysis of the muscles that are needed for well-directed pinch force, individuals with SCIs likely have more misdirected thumb-tip force during key pinch compared to nonimpaired subjects [21,22]. Surgeons regularly identify such problems and correct them; however, the extent of the functional deficit has not been adequately investigated. It is difficult to define general functional requirements for this, because the requirements for accurate positioning of the thumb relative to the index finger and accurate direction of the resulting pinch forces are influenced by the shape and size of the object to be grasped [23].

The use of the hand also depends on strength, control, and posture of the more proximal arm joints (not measured in this study) [24]. Future assessments of pinch function requirements should include values for force magnitude at specific pinch openings, precision of force location, precision of force direction, and proximal joint control requirements.

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