

Mechanical Comparison of Terminal Devices

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Introduction

Considerable controversy has developed over the appropriateness of fitting "functional hand" prostheses to juvenile and adolescent amputees. This controversy is further enhanced by the cosmetic advantages of functional hands over the more traditional hook terminal devices. Conversely, experience has shown the hook terminal devices to offer greater functional control. Prosthetists often feel obliged to fit the amputee with a more functional terminal device, while the amputee often wishes to relinquish some function for cosmesis. Because the functional hands available today do not approach the necessary control, and because hooks are so uncosmetic, a significant percentage of upper limb amputees tend not to wear their prosthesis. The fundamental question presented to the prosthetist in fitting an amputee is how much function can be gained with a particular device. If function is defined simply as prehension grip force and grip width, the next question is whether an amputee can fully operate the particular device completely and comfortably.

To date, very little objective data has been available on the comparison of terminal devices. Hence, prescription principles on the part of most prosthetists have been somewhat subjective. Quantitative force and excursion are not usually critical in fitting low level amputees; but the strength adolescents, juveniles,

and higher-level adult amputees can induce, becomes quite variable. The study presented here is an objective comparison of several terminal devices for mechanical function. The measured parameters were prehension grip force, grip width at full open, excursion range, and the excursion force required to fully open the terminal devices.

Methods

Test Protocol

All test data presented here was accomplished on a MTS-858 universal materials testing machine. With this hydraulically powered machine, a piston-like cross-head can be positioned accurately, while loads created on the test specimens are monitored. The degree of sophistication of this machine is not critical to the test protocol. Any testing apparatus can be used as long as displacement and created force can be measured accurately.

Two different tests were performed on each terminal device at each of the different tension settings available. The first test will be referred to as the excursion test. Here, the cross head and load cell of the test machine were attached to the cable actuator of the terminal device (Figure 1). The terminal device itself was mounted rigidly to the machine base. The result of this test was a plot of excursion of the cable actuator against the tensile force gener-

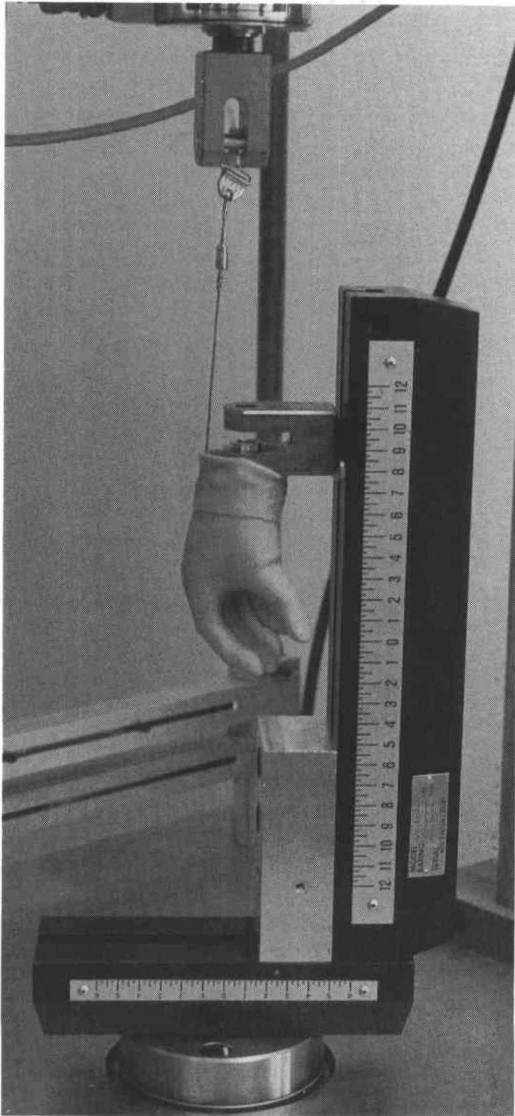


Figure 1. A 2.5" U.N.B. STEEPER set up for excursion testing on the MTS-858 universal machine.

ated in pulling the cable (Figure 2). The rate of pull was constant at 4" per minute and, because of this slow rate, loading was considered to be static. The plots of excursion force versus excursion of the cable actuator were all of the same general form. Figure 3 shows generalized force versus excursion plot. To present the actual loading curves for each device tested would have taken considerable space, therefore, for each device the only parameters that were tabulated are "A," "B," "C," "D," and "E." The portion of the curve up to "A," "C," represents the pre-loading of the terminal device. Excursion of the cable up to this point does not significantly move the appendages of the terminal device and is primarily due to slack in the system. The pre-load force "C," is the force necessary to overcome preloading of the spring or bands. The force constant "D," of a particular terminal device is the slope of the loading curve between the end of pre-loading and full open excursion of the cable. The full open excursion of the cable actuator is the distance "B," while the force required to fully open the device is labeled "E." It should be noted that with the five parameters, an estimation of the excursion-load curve of a particular device can be reconstructed. It should also be noted that the tabulated excursion parameters were measured by pulling the terminal devices open. If one was to continue to plot force versus excursion while the device was allowed to close, one would find much lower forces for a given excursion. This hysteresis in the loading curve is due primarily to friction. The loading curves are presented, rather than the unloading curves, because this is the manner in which the devices are operated.

The second test performed was to assess the prehension gripping forces that are created with each device. With the hand in a horizontal position, the base of the test machine was attached to the thumb, or one hook half, with a cable. The phalanges, or other hook half, were attached to the cross head and load cell of the test machine via a cable (Figure 4). The prosthesis was started in the full open position. A plot of grip force versus grip width was created by allowing the device to close at a constant rate of 4" per minute (Figure 5). From these plots, the parameters "G," "H," and "I," were calculated for use with the generalized graph (Figure 6). It should be noted that the

Excursion
Force (lbs)

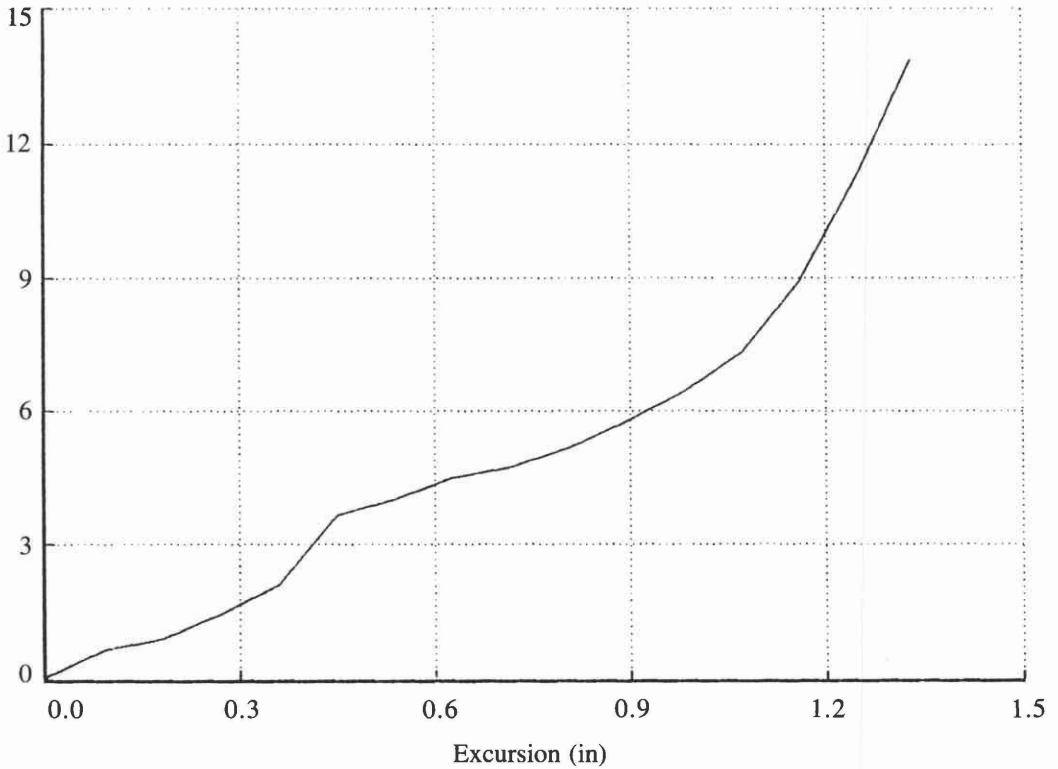


Figure 2. Experimental plot of excursion force vs. excursion travel on a 2.5" U.N.B. STEEPER terminal device. Notice that at 0.45" the characteristics of the curve changes. This is the point (A,C) at which the hand just begins to open.

Excursion
Force (lbs.)

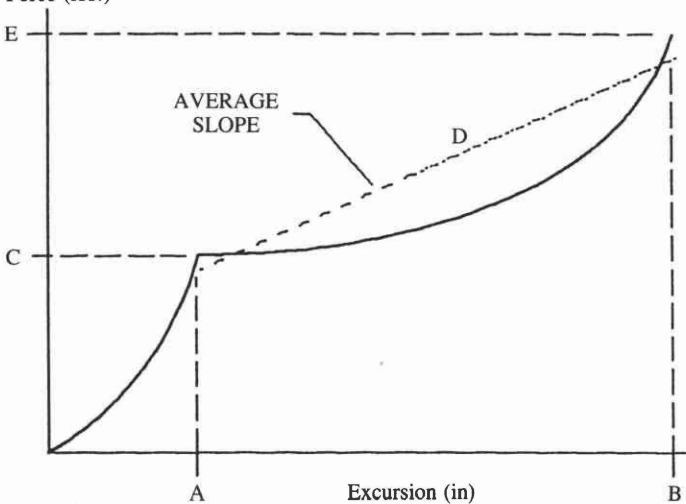


Figure 3. Generalized version of excursion force vs. excursion with parameters indicated.

- A—Pre-load excursion (inches)
- B—Full opening excursion (inches)
- C—Pre-loading force (lb.)
- D—Force constant in loading (lb./in.)
- E—Total excursion force at full open (lb.)

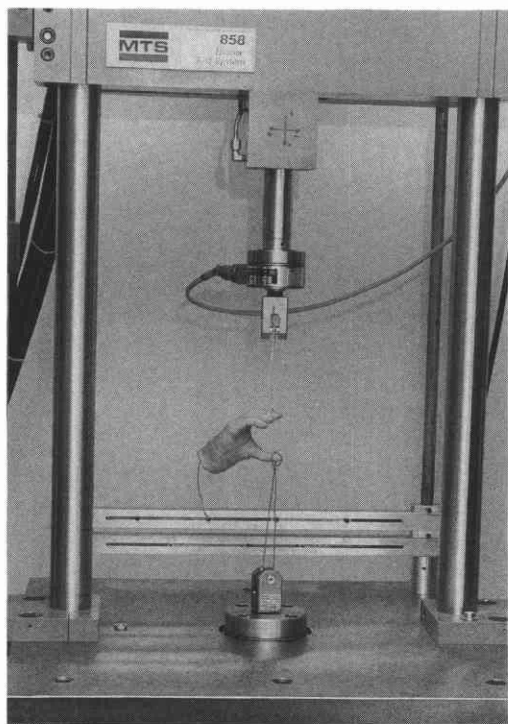


Figure 4. A 2.5" U.N.B. STEEPER set up for prehension grip testing on the MTS-858 universal machine.

plotting direction of these curves was opposite to those discussed in Figures 2 and 3. Since the hand was started full open, maximum prehension grip force "I" and the full open grip width "F" are plotted first. The force plotted here represents the force created by the device upon its own closing. The force necessary to pull the appendages open would be greater than this force, due to friction. In Figure 6, "G" is referred to as the initial prehension force. This is the force created just prior to the grip closing completely. Also, the prehension grip force constant, "H" is the slope of the unloading curve between fully open and closed positions of the terminal device. With the parameters "F," "G," "H," and "I," an approximate reproduction of prehension grip force verses grip width can be created.

Results

Table I lists the measured parameters derived from the two tests of 33 terminal devices. Of the 12 parameters listed, the first nine were described previously in the test protocol section. The J-th parameter is the number of different devices tested of each type. When more than one device was tested of a particular type, results were averaged. The criteria for testing most of the devices was based on local availability. The ratio of maximum prehension grip force to excursion force is often called the efficiency of a terminal device. The K-th parameter is the measured efficiency. The last parameter, listed as "L," is that of the work required to open the terminal device by pulling the actuator cable. Work is defined as the excursion force times excursion length and is measured by calculating the area under the force-excision curve. This parameter can be estimated to reasonable accuracy by considering the area under the generalized force-excision curve (Figure 3). The work, or area under this curve can be calculated as:

$$\text{work} = \frac{1}{2}(A \cdot C) + (B - A)C + \frac{1}{2}(E - C)(B - A)$$

Discussion

General trends in the measured parameters become evident on closer examination of Table I. Organization of these tables is such that devices with numbers less than 20 were hook type terminal devices, while those with numbers 20 and over were functional hands. Preload excursion, parameter "A," can be thought of as the excursion necessary to take up slack in the system. Some functional hand units require as much as 1/2" of excursion before any opening occurs. Full opening excursion, parameter "B," and the total excursion force necessary to open the terminal device, parameter "E," are self explanatory. If an amputee cannot generate either the excursion or the necessary force, a different terminal device should be considered. It should be noted that children usually have trouble operating a device with an excursion force greater than ten pounds.

The pre-loading force "C" and the force constant "D" are useful parameters in as-

Prehension Grip
Force (lbs.)

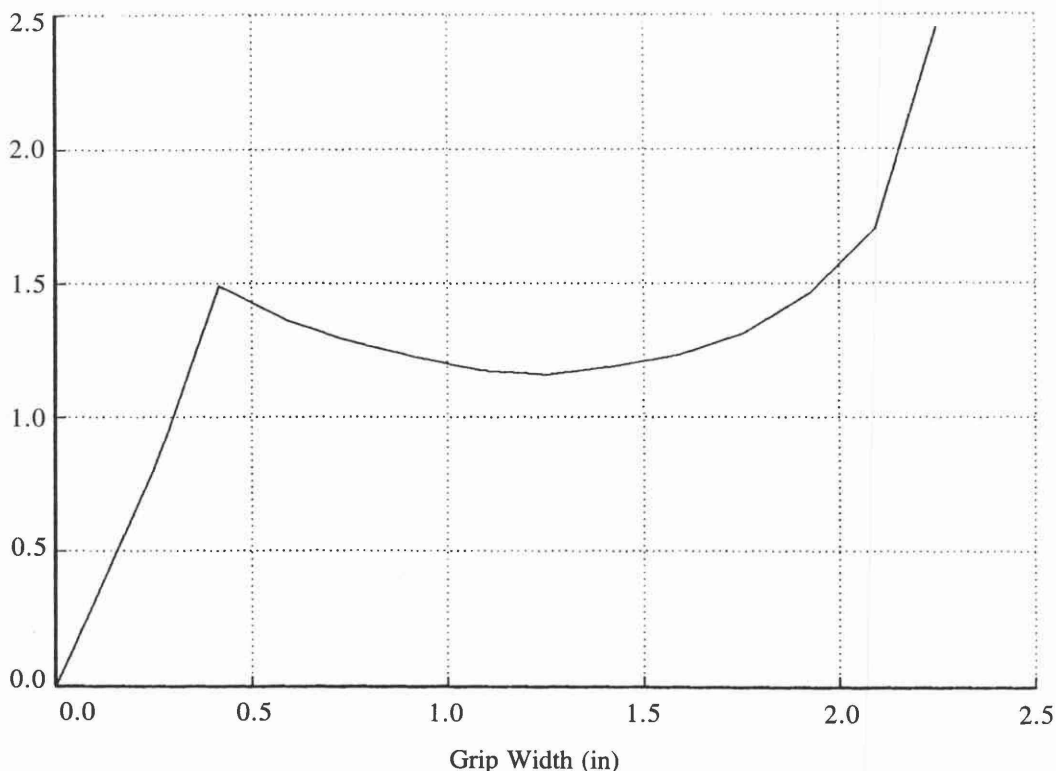


Figure 5. Experimental plot of prehension grip force vs. grip width for a 2.5" U.N.B. STEEPER. This plot was started with the hand full open, a 2.25" grip width, and 2.5 lb. grip force. The steep slope at approximately 0.4" is where the inner locking mechanism activates. The hand is essentially closed at this time.

sessing the function of a terminal device when the amputee can marginally create the forces and excursion necessary for full opening. In marginal cases, large pre-loading forces will limit the function of a device. For example, although the UCLA CAPP, device number one, only takes eight pounds to open fully, a patient must be able to create at least 4.5 pounds to start the device in motion. Without regard for the pre-load, one might incorrectly think that four pounds of excursion force would open the device halfway. A terminal device with a high pre-opening excursion (more prominent in hands) could be used on an amputee with good strength initially, but might have weakness toward the end of the excursion range. This is

particularly true for higher levels of amputation which rely more on scapular abduction and less humeral flexion. Another important factor to note is the grip performance of the terminal devices. Here the full open grip width "F" and maximum prehension grip force "I" are the important notable values.

The parameter that includes both grip and excursion is "K," the ratio of maximum grip force to excursion force. This term was measured to be greater than 0.40 for all of the hook type devices examined, and less than 0.40 for the functional hands. Some hooks revealed efficiencies as high as 0.70. It should be noted that the ratio of maximum grip force to excursion force can be calculated from the geometry

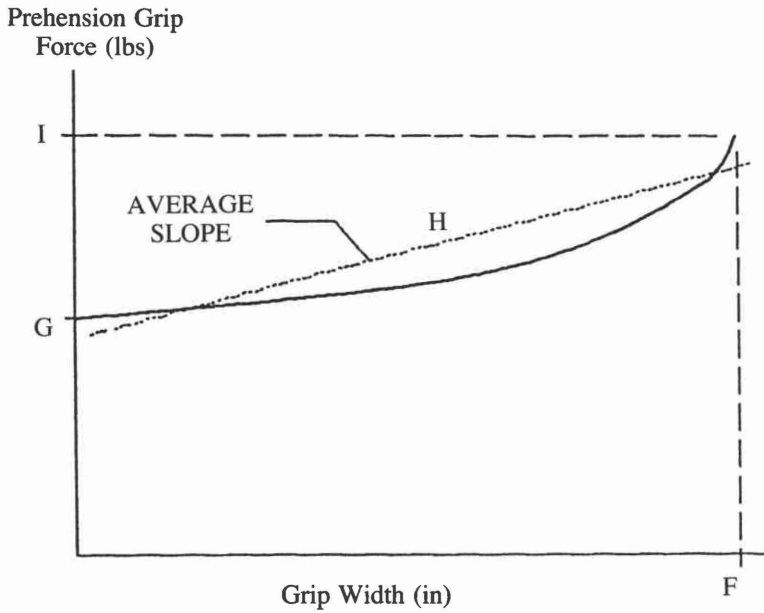


Figure 6. Generalized version of prehension grip force vs. grip width, with parameters listed.

- F—Full opening grip width (inches)
- G—Initial prehension grip force (lb.)
- H—Prehension grip force constant (lb./in.)
- I—Total prehension grip force (lb.)

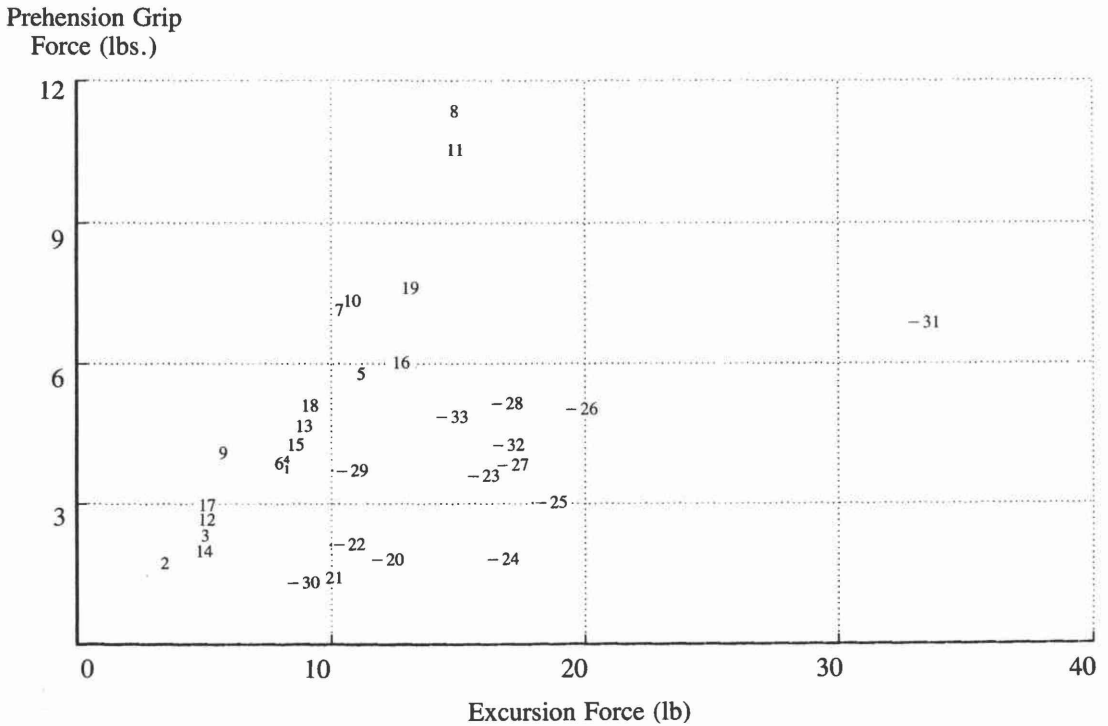


Figure 7. Graph of prehension grip force vs. excursion force for all terminal devices. Note that all hand terminal devices have a preceding dash.

Device Number	1	2	3	4	5	6	7	8	9	10	11
A. Pre-load Excursion (in)	0.25	0.06	0.12	0.12	0.12	0.03	0.06	0.06	0.06	0.12	0.12
B. Full Opening Excursion (in)	1.75	1.68	2.06	2.06	2.06	1.87	1.87	1.87	1.87	1.87	1.87
C. Pre-loading Force (lbs)	4.50	1.80	3.80	7.25	10.50	5.40	6.00	9.60	2.50	6.00	8.50
D. Force Constant In Loading (lbs/in)	2.30	0.90	0.50	0.36	0.25	1.30	2.30	2.80	1.60	2.50	3.40
E. Total Excursion Force Needed to Open Terminal Device (lbs)	7.95	3.26	4.77	7.95	11.00	7.80	10.16	14.67	5.40	10.37	14.45
F. Full Opening Grip width (in)	3.00	3.00	4.00	4.00	4.00	2.37	2.37	2.37	2.25	2.25	2.25
G. Initial Prehension Grip Force (lbs)	0.75	0.36	0.92	2.08	3.46	1.55	3.49	5.77	1.48	3.42	5.26
H. Prehension Grip Force Constant (lbs/in)	1.00	0.42	0.30	0.47	0.55	0.97	1.50	2.30	1.10	1.70	2.30
I. Maximum Prehension Grip Force (lbs)	3.75	1.62	2.12	3.96	5.66	3.85	7.05	11.22	3.96	7.25	10.44
J. Number of Hands Tested	2.00	3.00	1.00	1.00	1.00	3.00	3.00	3.00	2.00	2.00	2.00
K. Efficiency: Ratio of Maximum Prehension Grip Force to Excursion Force	0.47	0.50	0.44	0.50	0.51	0.49	0.69	0.76	0.73	0.70	0.72
L. Excursion Work (lb-in)	9.90	4.15	8.54	15.18	21.49	12.23	14.80	22.25	7.22	14.68	20.59

Table I. Values measured from hook and hand type terminal devices.

Description of Terminal Devices Tested

The following list of terminal devices corresponds to the device number of Table I.

1. CAPP regular spring, center pull, nylon cabled
2. CAPP soft spring, center pull, nylon cabled
3. HOSMER SSS-555, 1 band, steel cabled
4. HOSMER SSS-555, 2 bands, steel cabled
5. HOSMER SSS-555, 3 bands, steel cabled
6. HOSMER 10P, 1 band, steel cabled
7. HOSMER 10P, 2 bands, steel cabled
8. HOSMER 10P, 3 bands, steel cabled
9. HOSMER 10X, 1 band, steel cabled
10. HOSMER 10X, 2 bands, steel cabled
11. HOSMER 10X, 3 bands, steel cabled

- 12. HOSMER 12P, 1 band, steel cabled
- 13. HOSMER 12P, 2 bands, steel cabled
- 14. HOSMER 88X, 1 band, steel cabled
- 15. HOSMER 88X, 2 bands, steel cabled
- 16. HOSMER 88X, 3 bands, steel cabled
- 17. HOSMER 99X, 1 band, steel cabled
- 18. HOSMER 99X, 2 bands, steel cabled
- 19. HOSMER 99X, 3 bands, steel cabled
- 20. U.N.B. STEEPER, 2.0" w/glove, nylon pull
- 21. U.N.B. STEEPER, 2.25" w/glove, tension #1 (softest), nylon pull
- 22. U.N.B. STEEPER, 2.25" w/glove, tension #2, nylon pull
- 23. U.N.B. STEEPER, 2.25" w/glove, tension #3, nylon pull
- 24. U.N.B. STEEPER, 2.50" w/glove, steel cabled
- 25. U.N.B. STEEPER, 2.75" w/glove, steel cabled
- 26. HOSMER SIERRA, gloved, steel cabled
- 27. HOSMER ROBINS-AIDS, soft-mechanical, gloved, steel cabled
- 28. HOSMER BECKER-IMPERIAL, gloved, steel cabled
- 29. HOSMER, #201 gloved, steel cabled
- 30. HOSMER, #301 gloved, steel cabled
- 31. HOSMER, #401 gloved, steel cabled
- 32. OTTO-BOCK, 6.75", gloved, steel cabled
- 33. OTTO-BOCK, 7.75" gloved, steel cabled

Device Number	12	13	14	15	16	17	18	19	20	21	22
A. Pre-load											
Excursion (in)	0.06	0.06	0.12	0.12	0.12	0.06	0.12	0.12	0.05	0.25	0.25
B. Full Opening											
Excursion (in)	1.31	1.31	1.75	1.75	1.75	1.87	1.87	1.87	0.87	0.87	0.87
C. Pre-loading											
Force (lbs)	1.20	2.80	3.10	6.20	10.10	3.50	7.70	12.00	3.00	4.00	4.50
D. Force Constant											
In Loading (lbs/in)	2.70	4.50	0.88	1.20	1.33	0.59	0.57	0.37	10.30	8.00	8.64
E. Total Excursion Force											
Needed to Open Terminal Device (lbs)	4.57	8.42	4.53	8.15	12.27	4.56	8.70	12.65	11.40	8.96	9.86
F. Full Opening											
Grip width (in)	1.50	1.50	3.37	3.37	3.37	3.00	3.00	3.00	1.75	2.00	2.00
G. Initial Prehension											
Grip Force (lbs)	0.96	1.79	0.95	2.15	3.38	1.20	2.48	4.33	0.00	0.00	2.00
H. Prehension Grip											
Force Constant (lbs/in)	1.20	1.80	0.31	0.60	0.75	0.54	0.84	1.06	0.98	0.65	0.00
I. Maximum Prehension											
Grip Force (lbs)	2.76	4.49	2.00	4.17	5.91	2.82	5.00	7.51	1.70	1.30	2.00
J. Number of											
Hands Tested	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00
K. Efficiency: Ratio of											
Maximum Prehension Grip Force to											
Excursion Force	0.60	0.53	0.44	0.51	0.48	0.62	0.57	0.59	0.15	0.14	0.20
L. Excursion Work											
(lb-in)	3.64	7.10	6.40	12.07	18.84	7.40	14.81	22.29	5.98	4.52	5.01

Table I (continued).

Device Number	23	24	25	26	27	28	29	30	31	32	33
A. Pre-load											
Excursion (in)	0.10	0.42	0.42	0.44	0.12	0.44	0.06	0.06	0.69	0.09	0.06
B. Full Opening											
Excursion (in)	0.87	1.35	1.50	1.44	1.31	2.06	1.37	1.31	1.62	1.75	2.75
C. Pre-loading											
Force (lbs)	7.50	4.20	5.50	7.50	8.50	13.25	2.75	2.50	15.25	3.75	3.75
D. Force Constant											
In Loading											
(lbs/in)	10.00	12.70	11.43	11.50	6.60	1.80	5.50	4.50	18.60	7.40	3.80
E. Total Excursion Force											
Needed to Open											
Terminal Device (lbs)	15.20	16.00	17.84	19.00	16.35	16.17	9.95	8.12	32.55	16.03	13.97
F. Full Opening											
Grip width (in)	2.00	2.25	2.50	1.50	2.00	3.25	2.50	2.50	2.50	1.87	2.50
G. Initial Prehension											
Grip Force (lbs)	1.10	1.47	2.65	0.64	0.30	1.44	2.85	1.20	6.75	1.83	3.24
H. Prehension Grip											
Force Constant											
(lbs/in)	1.20	0.10	0.10	2.70	1.70	1.10	0.30	0.00	0.00	1.20	0.60
I. Maximum Prehension											
Grip Force (lbs)	3.50	1.70	2.90	4.95	3.70	5.02	3.60	1.20	6.75	4.07	4.74
J. Number of											
Hands Tested	1.00	2.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	3.00	3.00
K. Efficiency: Ratio of											
Maximum Prehension											
Grip Force to											
Excursion Force	0.23	0.11	0.16	0.39	0.22	0.31	0.36	0.15	0.21	0.25	0.34
L. Excursion Work											
(lb-in)	9.11	10.28	13.76	14.90	15.30	26.75	8.40	6.71	27.49	16.59	23.95

Table I (continued).

of a particular device and is independent of the spring or rubber band tension. The measured results show this to be the case, in that parameter "K" did not significantly vary when spring tensions or the number of rubber bands were changed. Measured efficiencies for the functional hands were, in general, less than hook terminal devices. This consistent discrepancy is due largely to friction in the mechanics of the internal hinges within the hands in addition to glove attachments.

The final parameter "L" which is the total amount of work required to operate the terminal device is also of extreme importance. Hands compare more favorably to hooks because on a general basis hands require less ex-

cursion than hooks for full opening. This is an important factor for children as well as higher levels of amputation, because of less available excursion.

Plotting maximum prehension grip force against total excursion force, the relative performance between hooks and hands can be compared (Figure 7). For clarity, the hand device numbers were plotted with a preceding dash. For any particular excursion force, it can be easily seen that grip force is greater for the hook devices. The devices 7, 8, 10, 11, and 19, were particularly good performers, which required excursion forces less than 15 pounds, and created prehension grip forces greater than seven pounds. In light of this comparison, it

should be challenging for terminal device designers to come up with functional hand devices that approach the efficiencies of hooks.

Conclusions

This comparison of terminal devices is only preliminary in that many more terminal devices have yet to be analyzed. Furthermore, the number of devices tested was very small. In spite of these limitations, the best protocol allowing comparisons between the different terminal devices was felt to be objective and re-

flect the relative performance of different devices.

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