N90-29037

RESPONSE TO REFLECTED-FORCE FEEDBACK TO FINGERS IN TELEOPERATIONS

P. H. Sutter, J. C. Iatridis, N. V. Thakor*
Franklin and Marshall College
Lancaster, PA 17604-3003
Dept. of Biomedical Engineering
Johns Hopkins University
Baltimore, MD 21205

Abstract

Reflected-force feedback is an important aspect of teleoperations. Our objective is to determine the ability of the human operator to respond to that force. The present study simulates telerobotics operation by computer control of a motor-driven device with capabilities for programmable force feedback and force measurement. We have developed a computer-controlled motor drive that provides forces against the fingers as well as (angular) position control. A load cell moves in a circular arc as it is pushed by a finger and measures reaction forces on the finger. The force exerted by the finger on the load cell and the angular position are digitized and recorded as a function of time by the computer. We investigated flexure forces of the index, long and ring fingers of the human hand in opposition to the motor driven load cell. We present results of the following experiments: 1) Exertion of maximum finger force as a function of angle; 2) Exertion of target finger force against a computer controlled force; 3) Test of the ability to move to a target force against a force that is a function of position.

Averaged over ten individuals, the maximum force that could be exerted by the index or long finger is about 50 Newtons, while that of the ring finger is about 40 Newtons. From our tests of the ability of a subject to exert a target force, we conclude that reflected-force feedback can be achieved with the direct kinesthetic perception of force without the use of tactile or visual clues.

1. Introduction

Space telerobotic systems[1,2] have many aspects, ranging from quite direct control by an operator in a master-slave configuration to much more autonomous control, which may be particularly useful when signal transmission times are large. We are concerned with the former, particularly the response of the human operator. Such a system might be used for work on a space station. An operator of a telerobotic system must be supplied with information on the status of the controlled device, perhaps an arm or manipulator. This information can be in the form of visual displays, audible or tactile signals, or reflected force feedback. Since knowledge of the forces experienced by the driven telerobotic system, as well as the position information, are of fundamental importance to the operator, it is useful to develop systems that feed that information back to the operator in as natural a way as possible. Our study is on the ability of a subject to respond to simple force signals to the fingers.

Each finger[3] has a metacarpal bone, which is inside the hand , and proximal, middle and distal phalanges. In our experiments, the metacarpalphalangeal (MCP) joint rotated in flexure. At high angles of rotation of the finger with respect to the straight ahead direction, the proximal interphalangeal (PIP) joint also rotated. The flexure forces are transmitted by tendons from muscles in the anterior forearm. The physiological basis for the perception of position and muscular force is discussed in review articles[4,5] on proprioception and kinesthetic sensations.

Reflected-force feedback to the fingers of an operator will be effective, if the operator can sense force levels in a normal way. This not only provides a more natural mode of perception by the operator but also frees up the other senses, for example vision, for other information gathering. In our experiments on the ability of a subject to sense forces, the computer provides a functional dependence of force on position that simulates the forces that might be felt by the slave unit in teleoperations in space.

2. Instrument Design

This study simulated telerobotics operation with a computer (IBM AT) which controls a dc motor (Galil control board) to provide angular position and torque control. Metrabyte DAS8 and Tecmar LabMaster boards were used for data acquisition. A semiconductor load cell was used to measure the force exerted by a finger on a computer controlled motor drive system that carried the load cell along a circular arc in a horizontal plane. Angular position was measured with an optical encoder and a potentiometer. The digitized force and position information was recorded in the computer as a function of time. Flexure forces exerted individually by the index, ring and long fingers of the human hand were measured as the finger pushed against the motor driven load cell, with the subject's arm and wrist stationary. The lower arm was horizontal, with the wrist and hand extended straight ahead. The upper arm was vertical. The apparatus is shown in Figure 1.

A one inch diameter brass "pad" was placed on the distal (terminal) phalanx of the finger being tested. It was soft on the side facing the finger and had a semicircular cross-section groove on the side that mated with the load cell holder. The straight groove in the pad bore against a steel rod on the outside of the load cell holder. Thus a force could be applied to the load cell with some freedom of motion of the finger with respect to the load cell. The steel rod was attached to a pivoted plate (see Figure 1) that held a block of teflon that actually pushed on the semiconductor load cell and assured that the forces exerted on the cell surface were perpendicular and uniform. The voltage output of the load cell was a linear function of the force. The voltage was digitized and converted to the force in Newtons by use of a gravity calibration method. In some experiments, a two inch long brass "splint" was used to restrict rotation to the MCP joint only. This mated with the load cell in the same way as the circular "pad".

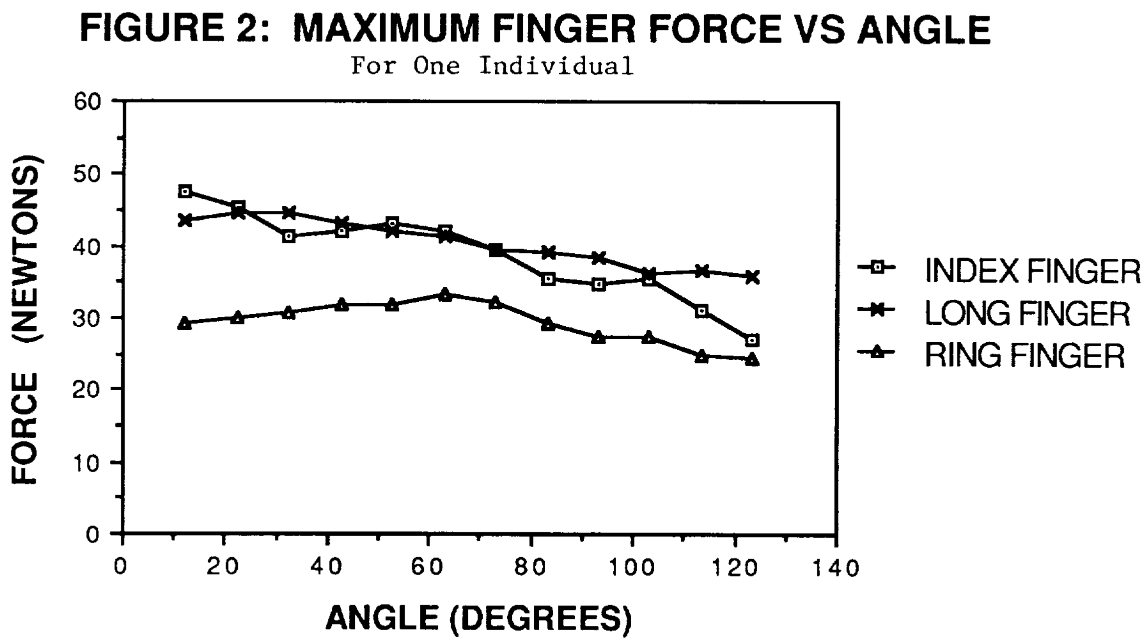
Figure 1: APPARATUS

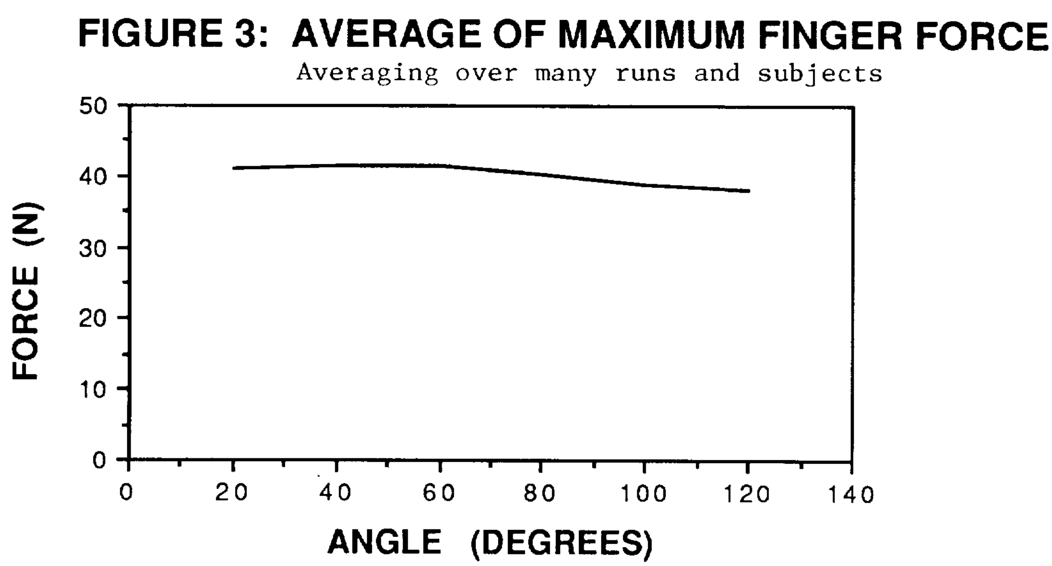
3. Experimental Results

3.1 Maximum finger flexion force:

We measured the maximum flexure force of the long, index and ring fingers of ten subjects. In one procedure, the motor drive swept the arm at a constant rate of 6.75 degrees per second for a time of 20.4 seconds. Data was obtained and recorded every 10 milliseconds. The subject exerted maximum force against the load cell with the pad on the terminal phalanx. This force deflected the arm slightly until the motor drive feedback torque became large enough so that the position was determined by the angle-sweep commands from the computer. The motor drive system was adequate to oppose the finger force and the angle increased as a linear function of time. Data from a single run is graphed in Figure 6 in the appendix. That data yields force and angle as a function of time after reduction based on the calibration of the apparatus. Figure 2 shows the maximum flexure force exerted by a finger as a function of angle for one individual. The three lines are for the index, long and ring fingers of this subject.

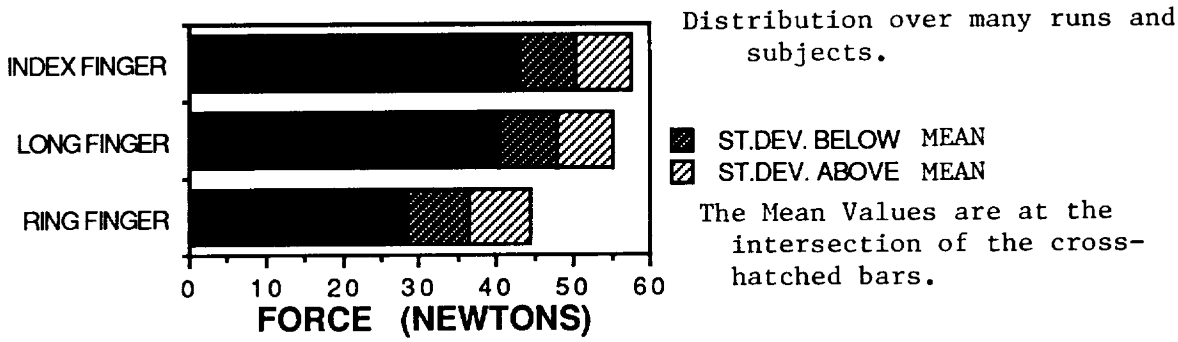
The finger angle is 0° when the finger is extended straight along a line through the forearm and hand. The subject's wrist was straight throughout the experiments . At first, only the metacarpophalangeal (MCP) joint rotates, but after about 70° the proximal interphalangeal (PIP) joint also rotates. Averaging over many runs and individuals yields a curve that is rather flat out to about 90° and then declines with increasing angle as shown in Figure 3.





The distribution over individuals is shown in Figure 4 in which the cross hatched segments of the bars represent a standard deviation above and below the mean, which is at the intersection of the cross hatched regions. For most individuals the index and ring fingers can exert approximately the same maximum force while the ring finger is weaker.

FIGURE 4: DISTRIBUTION OF MAXIMUM FORCE



3.2 Pulsed maximum force:

A second mode of testing was to have the computer sweep the angle range over a time interval of 40.8 seconds with the subject intermittently applying a maximum force. Data was obtained and recorded every 20 milliseconds. Typically, a signal tone was on for 3 seconds and then off for 3 seconds, etc.; and the subject exerted a maximum force when the tone was on and relaxed when it was off. This reduced the effect of muscle fatigue. The force versus angle was similar to the above graphs, with somewhat less decline at high angles. The higher angles occur at longer times so that part (but not all) of the decline at high angles in Section 3.1 may be due to fatigue.

In order to prevent rotation of the PIP joint, we also used a splint on the fingers of some subjects. The metal splint replaced the circular pad in bearing against the load cell device. The results were similar to those discussed above except that the finger rotation was limited to about 80°.

3.3 Target finger force:

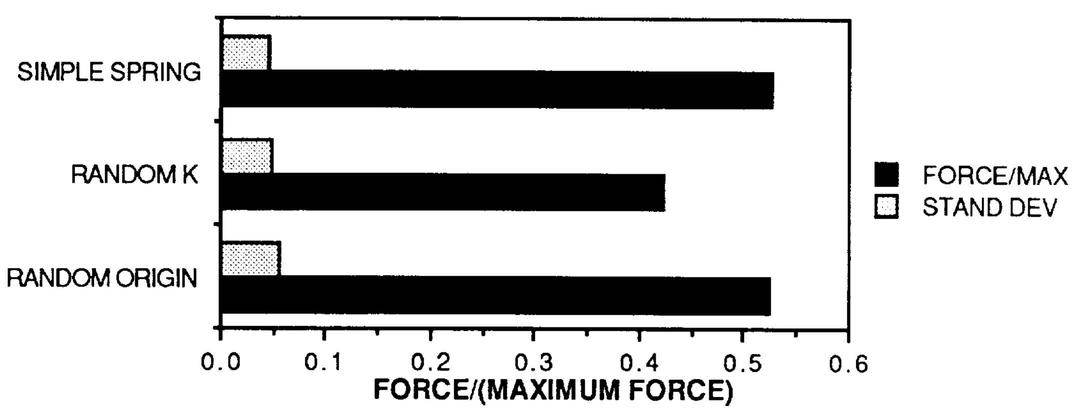
A series of experiments were designed to determine how well a subject could sense target force levels. In one set of experiments, the computer simulated a spring-like force. That is the restoring force was proportional to the distance from an origin. In this series, a subject heard a three second tone about once every six seconds and was told to push with the target force while the tone was on. The target force was half-maximum, quarter-maximum or eighth-maximum. A typical run consisted of the subject pushing at full maximum during the first tone and then, on the remaining tones, pushing at half maximum force. The repeatability of the force pulses was of primary concern, while the relationship to the maximum force was secondary. In the simple spring simulation, the computer selects a spring force constant and uses an origin near an angle of

0°. As the subject pushes against the load cell, the load cell moves through an angle while providing a restoring force that is proportional to the angular displacement from the origin. The finger might swing through an angle of forty degrees, for example, before the subject sensed the target force and held that force. The spring force constant and origin remain fixed during a single run. In each such run, the subject attempted to return to a target force 6 times. In a typical set of eight such runs, the ratio of the actual force to the maximum force was 0.46 ± .04 while the target was 0.50. The scatter of the 6 force pulses within a run was 7% ± 3%., which is .032± .014 with respect to the maximum force. For this simple spring simulation, the repeated return to the target force occurs at the same angular position during a run. Although the subject did not use vision to return to this repeated position, a proprioceptive sense could have been used rather than a perception of the force exerted by the finger.

3.4 Target finger force with separation of position and force sensing:

In order to separate the proprioception from the kinesthetic sense of force, we also simulated springs in which the spring constant or origin were randomized within a run. In these runs, the target force occurs at random angular positions during a run. Hence, the subject could not use position clues as a means of returning to the target force. Raw data for a run of this type is graphed in Figure 7 in the appendix. Since the vertical voltage scale is linearly related to the force, this data shows that the subject was able to closely return to the target force in successive attempts. The bar chart in Figure 5 shows the results of a series of runs with the index finger of a subject. Within each run, the computer simulated either a simple spring, a spring with random force constant or a spring with random origin. The long dark bar indicates the average ratio of the exerted force to the maximum force, with the target value being 0.50. The lighter bars show the average standard deviation of the scatter within a run, expressed as a fraction of the maximum force. We conclude that the subject is not relying on a position clue, but rather is correctly judging the force exerted by the finger.

FIGURE 5: HALF-MAX TARGET WITH SIMULATED SPRING



"RANDOM K" means random force constant or stiffness during a run.
"STAND DEV" means the standard deviation of the scatter within a run.

In order to study this force judgement at lower fractions of the maximum finger force, subjects attempted to repeat similar runs with a) a maximum force pulse followed by six attempts at a force of half-maximum; b) a first half-maximum force pulse followed by six quarter-maximum pulses; c) a first quarter-maximum pulse followed by eighth-maximum pulses. Table 1 shows the results of a series of these runs:

Table 1: Pulsed Target Forces Against Spring Simulations

		Mean successive/first		
First force	6 successive forces	Target	Observed	Scatter
Maximum	Half-maximum	0.50	0.48	± .05
Half-Max	Quarter-Max	0.50	0.44	± .05
Quarter-Max	Eighth-Max	0.50	0.34	± .05

The last column of Table 1 is the average scatter (standard deviation) within a run. This is expressed as a ratio to the force in the first pulse. The individual runs within a set included simple spring, random spring constant and random origin with results similar to those given above. The perception of the finger-force appears to be successful even at relatively low force levels.

3.5 Tactile clues:

The possibility that the force perception is simply due to tactile clues should be considered. For this purpose we repeated the runs with the use of the metal splint, which should reduce the pressure on the terminal phalanx and isolate the rotation to the PIP joint. The results were similar as long as the splint did not impede the motion with the least stiff spring simulations. These results are shown in Table 2:

Table 2. Pulsed Target Forces with Splint

		Mean successive/first		
First force	6 successive forces	Target	Observed	Scatter
Maximum	Half-maximum	0.50	0.42	± .05
Half-Max	Quarter-Max	0.50	0.46	± .05
Quarter-Max	Eighth-Max	0.50	0.45	± .04

As another way to reduce the tactile sensation of force, we immersed the terminal phalanx of the finger in ice for about ten minutes before repeating the runs. The finger was re-inserted in the ice for several minutes between runs, each of which took about 40 seconds. The results are given in Table 3:

Table 3: Pulsed Target Force with Numbed Finger
First pulse was maximum, successive six pulses were half-maximum.

	Mean of successive forces/first force			
Spring simulation	No Ice	Scatter	With Ice	Scatter
Fixed force constant	0.46	± .05	0.42	± .04
Random force constant	0.34	± .05	0.35	± .05

The results indicate that numbing the terminal phalanx of the finger, which is in the pad that pushes on the load cell, does not prevent the perception of force. We conclude that this force perception is not an artifact of tactile clues at the finger tips.

4. Conclusions

Based on the results in Section 3.1 and 3.2, it appears that a good design value for the maximum finger force to be exerted by an operator in a telerobotics system is about 40 Newtons for the index and long fingers and about 30 Newtons for the ring finger. These forces can be maintained out to angular excursions beyond 90 degrees. Averaging over runs and individuals, the maximum finger flexure force is nearly independent of angle in this range.

From the results in Section 3.3 and 3.4, we conclude that a subject can successfully exert a target force against a restoring force which is a function of position. The ability to repeatedly sense the target force level did not require visual or position information and did not require training.Furthermore, the perception of force was effective down to one-eighth of the maximum force. From the experiments described in Section 3.5, we conclude that the perception of the force exerted by a finger is not dependent on tactile clues.

This study is encouraging with respect to the use of direct operator perception of force in reflected-force feedback telerobotic devices. This can be useful in developing space telerobotics because it provides natural perception of force by the operator rather that a reliance on visual displays, for example, which might then be used for other information.

References

1. Antal K. Bejczy "Sensors, Controls, and Man-machine Interface for Advanced Teleoperation", Science 208, 1327 (1980)
2. R.L.Smith and D.J.Gillan, "Telerobotics in Space: Some Human Factor Considerations", ISA, 307-314, 1987
3. J.C.Becker, N.V.Thakor and K.G.Gruben, "A Study of Human Hand Tendon Kinematics with Applications to Robot Hand Design", IEEE Conference on Robotics and Automation, 1-6, 1986
4. W.J. Williams, "A Systems-Oriented Evaluation of the Role of Joint Receptors and other Afferents in Position and Motion Sense", CRC Critical Review in Biomedical Engineering, Dec.1981
5. P.B.C.Matthews, "Where Does Sherrington's 'Muscular Sense' Originate? Muscles, Joints, Corollary Discharges?",Ann. Rev. Neuroscience 5, 189, 1982.

Acknowledgement:

This work was supported by the Johns Hopkins University -Dana Foundation Sabbatical Program at the Department of Biomedical Engineering of Johns Hopkins University.

APPENDIX

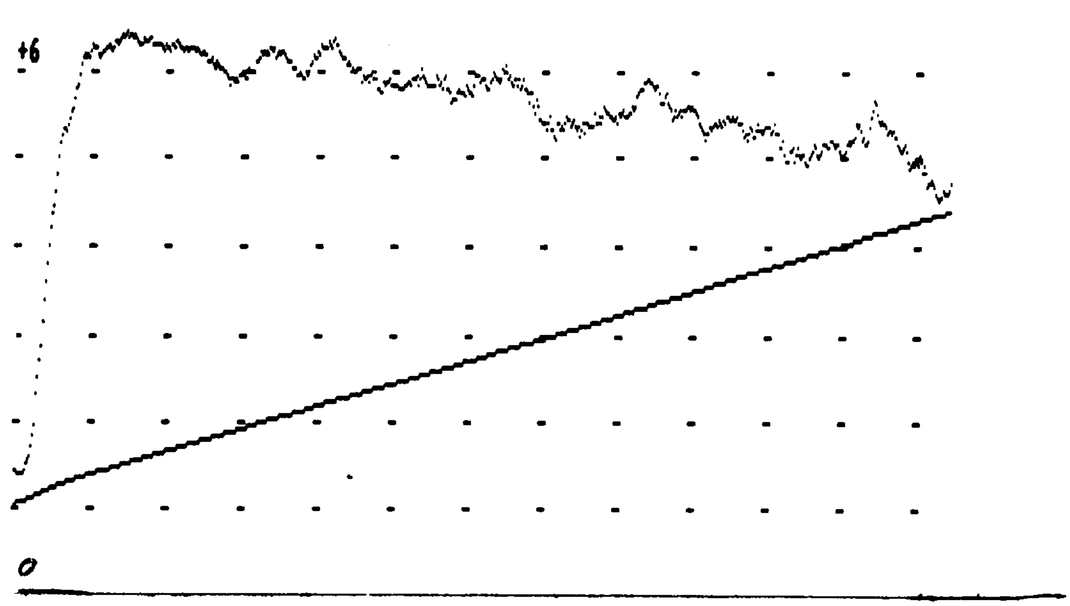


FIGURE 6 Raw Data for Force and Position versus Time.
The load cell voltage is plotted vertically with a scale of one volt per dot. 6 volts corresponds to a force of 42 Newtons. The dots are 1.5 seconds apart horizontally. The dotted line is position versus time with the motor drive providing a constant sweep rate under computer control at about 10^{o} per dot.

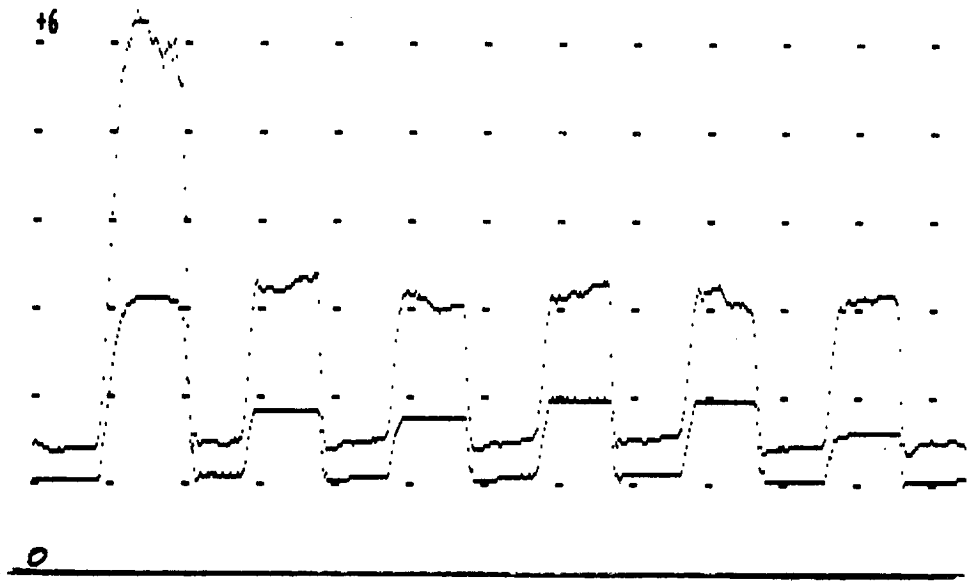


FIGURE 7 Raw Data for Target Finger Force Against a Simulated Spring. This simulation is for a spring with a random spring constant so that the stiffness of the spring changes randomly at each attempt. The dots are three seconds apart horizontally. The subject pushes for about three seconds and then relaxes for about three seconds. The first pulse target was maximum force and the load cell voltage reached about 6 volts which corresponds to 42 Newtons. The lower plateau at that time is the position data. On the following attempts the target force was half-maximum. Notice that the force levels are similar but that the lower plateau for position is variable. This is because the system behaved like a spring with a random stiffness. The subject pushes out to the same force level even though it occurs at different positions.