Finger Force Precision for Computer Pointing

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ABSTRACT

This paper addresses motor control constraints which affect analog pointing devices used with computer interfaces. We have investigated the accuracy and precision with which subjects can apply force to a small isometric joystick with a fingertip or finger and thumb, for one and two dimensional force specification.

We find the information content of a force application to be in the range of 4 to 6 bits per dimension with visual feedback, and without time constraint. The force application task in two dimensions is no more difficult than in one dimension and gives twice the information content. Use of an opposing thumb and finger gives no improvement over a single finger. Both inaccuracy and imprecision are concentrated along the direction of the specified force - subjects tend to be both more accurate and more precise in the direction of force than in its magnitude.

Implications for analog pointing devices are discussed.

KEYWORDS

Mouse, Joystick, Dexterity, Force Precision

INTRODUCTION

Recent work [5, 7] has demonstrated that pointing performance can be significantly improved when human motor-perceptual limitations are taken into account.

This reopens questions of strategies for physical control posed at the time of radio knob design, etc. [2-4, 8] What are the perceptual motor constraints of physical control design? How should these constraints affect the relationship between the physical control and a machine's response to its movement? By understanding the relationships between these information channels we can improve design interfaces.

Motivated by work in designing a finger pressure controlled pointer, we wanted to understand the control channels available to various analog motor tasks. We report here a study of the finger-pressure channel. We have considered visual, auditory, tactile and proprioceptive feedback. Some tactile feed back is inevitably present (barring anesthesia). Preliminary experiments indicated that auditory feedback alone is much less effective than visual, even in the one-dimensional case, while tactile feedback alone appears to allow less than 3 bits in each dimension. This study focuses on finger pressure with tactile and visual feedback, without time constraint. The subject may take several seconds to apply the specified force, and the force is then measured as the mean of instantaneous forces sampled over a 2.4 second integrating period. Even under these conditions accuracy and precision are surprisingly low.

The force range which we have investigated is that appropriate for one or two fingers on a small sensor (a 3 mm by 8 mm cylinder), 0 - 225 grams.

While there are many studies of complex tasks such as pointing and tracking which use the finger or hand force channel, there seem to be few if any which address the accuracy and precision available in the channel itself. We have found only [6], which studies whole arm movements at much greater forces. His studies found subjects could apply a arm force to within 10percent of a attempted target force.

METHOD

Apparatus

Subjects were seated at a standard office desk, in a chair adjusted to comfortable height by the subject. On the desk were a CRT display and a 101-key IBM PS/2 keyboard, placed about 10 cm back from the edge of the desk. In the center of the keyboard, between the G and H keys, was an isometric joystick (the same sensor used in the Pointing Stick, [5]) topped by a dished 3x5 mm diameter finger rest, 4 mm above the level of the key caps Figure 1. The joystick top moves an undetectable .13 mm at maximum force.

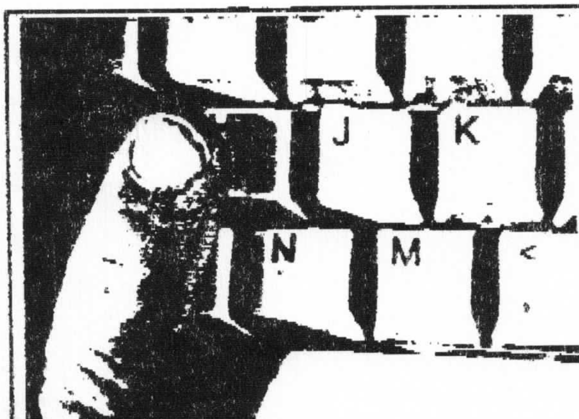

Figure 1. Fingertip grip of an isometric joystick

An IBM 8514 in VGA graphics mode .4 mm square pixels on a 480 by 640 screen

For the fingertip grip condition the subject placed a finger tip on the finger rest. For pen grip experiments, adjoining key caps were removed exposing an 8 mm long 3 mm diameter "pen", grasped between thumb and forefinger. Figure 2

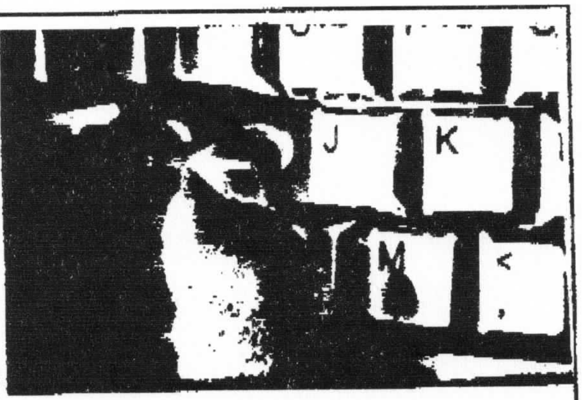

Figure 2. Pen style grasp of an isometric joystick

Experiments were also run using a single finger or thumb pressure on the side of the joystick to understand the value of the opposing digit in the pen grip condition. This is called the side grip.

Strain gauge signals from the sensor were processed to produce signals on an IBM PS/2 pointing device interface such that the resulting cursor position represented the horizontal force being applied to the sensor, within the limits of the display screen. Strain gauge sensing and signal processing was performed by a separate IBM PC/XT with a Scientific Systems Labmaster data acquisition board which communicated to the PS/2 through its mouse port.

A program running on a IBM PS/2 model 80 presented stimuli, provided feedback, and recorded data.

Subjects
Over several month periods one subject performed experiments to calibrate and develop data collection techniques.

We report here on results from four subjects, hired through an agency as office temporaries. They all normally work in secretarial and clerical jobs, frequently using word processors, and had slight familiarity with mice, but no prior experience with other computer pointing devices. All were women, between 25 and "50's", who reported typing speeds between 50 to 80 words per minute. Two played or had played a musical instrument; no other high-manual-dexterity hobbies were reported. Subjects participated in these experiments as part of a two-day sequence of experiments on pointing behavior, using the Pointing Stick in its normal mode and a mouse in addition to the present apparatus.

Procedure
The experimental paradigm is as follows: Subject initiates each trial with a keypress. A target force is presented as a position on the screen. The subject attempts to apply the specified force, by bringing the cursor to the target and holding it there.

An initial movement towards the target is ended when the subject's precision limit is inevitably reached and the cursor moves away from the target. During the following "hold" phase the cursor is held as stably as possible for some 2.4 seconds. The mean applied force during the "hold" phase will be called the trial's effective force and its standard deviation is taken as the trial's imprecision or dither. The miss vector is the difference between the target vector and the effective force vector. The miss angle is the direction of the miss vector.

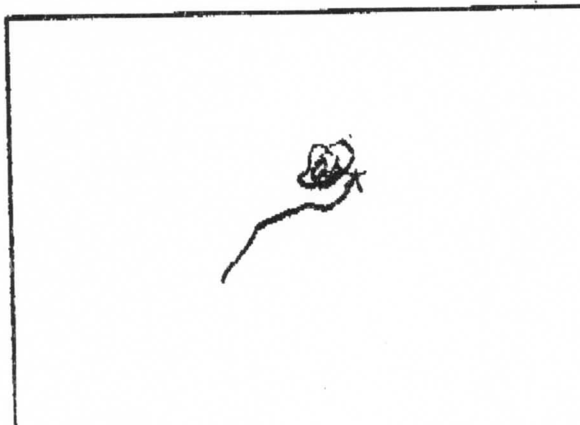

Figure 3. Display showing stability and accuracy of force application in a trial.

Feedback information is added to the target display at the end of each trial. The computer displays the track of the cursor's movement. A cross on the track marks the beginning of the hold phase and an ellipse is centered at the mean hit position with shape representing the variation in applied force during the hold phase.

Separating subjects target selections from target hold phase is exemplified in Figure 3. In this figure it is noticeable that after a subject attempts to select a target, stability at holding the requested force can be characterized as a cloud of dither.

After 10 such trials the computer displayed numbers indicating relative accuracy and relative dither and standard deviations for the group of trials. A menu selection is selected to run ten groups of these.

The subjects performed these the trial type doing two dimensional (circle) targets, vertical one dimensional, and horizontal one dimensional targets. All of these conditions were investigated for the finger tip as well as pen grip conditions. A nominal 300 trials were collected for each two dimensional condition and a nominal 100 were collected for each one dimensional condition. For two subjects an additional nominal 100 trials were collected for the side grip condition.

Target forces were pseudo-random, with uniform distribution over the range corresponding to the display screen, excluding an approximately 1 cm margin and a disk of diameter 2 cm in the center.

An experimenter remained in the room to observe and to demonstrate protocols. Written instructions explained each phase of the experiment, and directed the sequence of phases; the sequence was varied in some cases to maintain subject motivation. The experimental protocol was otherwise administered and results recorded by the computer.

RESULTS

Target force, mean applied force, dither, and time were recorded for each trial. Initial sets of trials were discarded, as were a few trials invalidated by interruptions or equipment problems. Table 1 gives overall averages of miss and dither for the three target types, and for the two grips. Figures 4 - 12 look at the data in more detail, examining dependencies on target force,

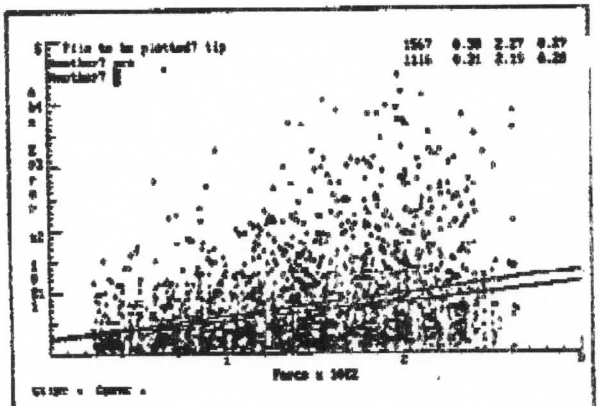

Figure 4. The relationship between distance and accuracy

Figure 4 plots error against target force for the two grip conditions. The figure shows that while absolute accuracy of force decreases with requested force, relative accuracy increases with force. The large range in accuracy indicated by the quite tall cloud shows that range in performance is wide. Note that the pen grip condition adds a slight advantage over the finger tip condition.

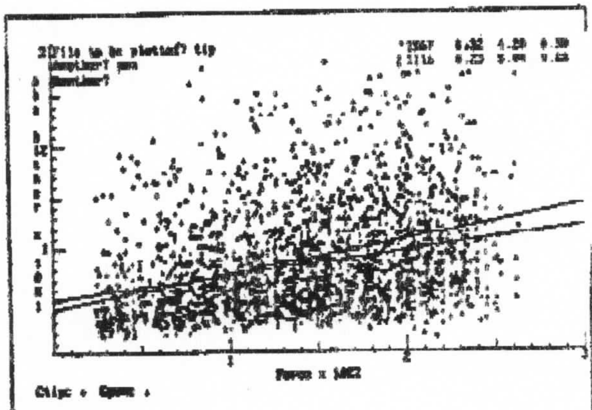

Figure 5. The relationship between force and steadiness

Figure 5 plots dither against force for the two grip conditions. Notice the blank area at the bottom of the screen. This represents a limit to steadiness. The width of this band shows that no one was able to hold force steady to within 2 grams. The average instability was 8 grams varying in individual from 5 to 12 grams. Like the error, dither also increased somewhat with force.

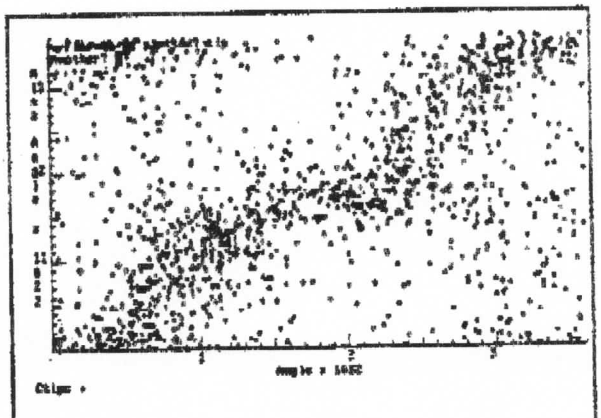

Figure 6. Direction of miss versus target direction

Figure 6 shows the relationship between the target direction and the miss angle. Note that the miss angle tends to be 180 degrees from the target angle showing that subjects tend to undershoot the target force. It shows that subjects were more accurate in the direction than in magnitude of force application. This data could be used to help design velocity transfer functions. Another use of this suggests that menus should be made "deep" in the direction of most likely approach. Edge menus, which are effectively infinitely deep, are instances of this.

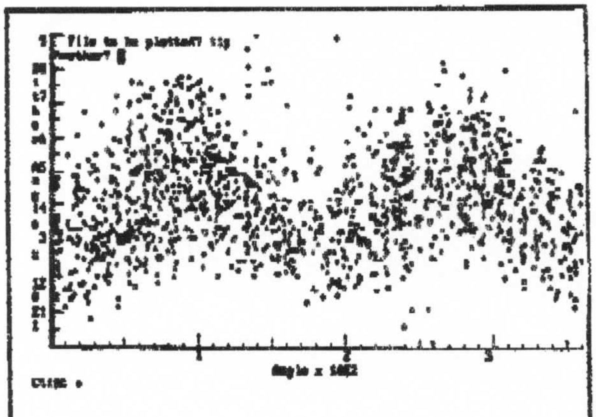

Figure 7. Stability in direction of target is worse than in orthogonal direction

A striking result emerges by looking at the shape of the data cloud of subject hold data, Figure 7. The ellipse that represents the mean of the dither cloud has approximately a 2 to 1 axis ratio in the direction of the target. We have collected data for pressure towards targets above below to the right and to the left. Our data collection procedure for angular forces does not distinguish this at other angles.

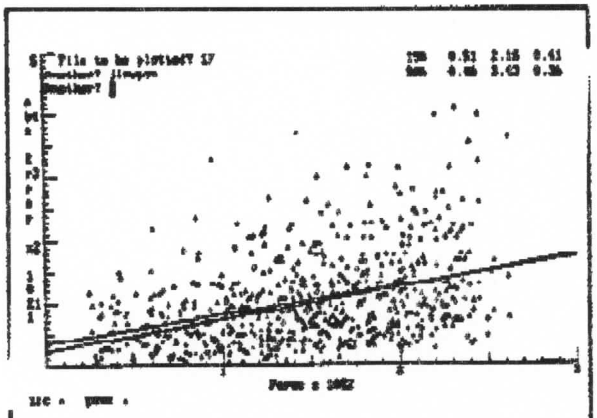

Figure 8. Demonstration that pen grip is not better than pushing with a side grip.

Experiments comparing the side grip to the pen grip test the role of opposing grip for pressure accuracy and stability Figure 8. Note that in the data the side grip is not distinguished from the pen grip. This suggests that the slight advantage of the pen grip condition over the tip grip is due to improvement in control by pushing on the side of the post rather than to any additional stability provided by another finger.

	Samples	Error	Dither
2 Dimensional			
Tip	1567	7.7	8.8
σ		7.8	6.0
Pen	1116	6.6	8.3
σ		6.1	5.2
1 Dimensional - Horizontal Bars			
Tip	389	4.5	6.0
σ		4.7	4.0
Pen	260	3.3	4.8
σ		4.3	4.2
Horizontal Projection of 2 Dimensional Data			
Tip	1510	5.3	6.2
σ		5.7	4.2
Pen	1074	4.7	6.2
σ		4.9	4.1
1 Dimensional - Vertical Bars			
Tip	390	5.1	5.6
σ		7.0	5.2
Pen	397	4.3	5.6
σ		4.9	4.4
Vertical Projection of 2 Dimensional Data			
Tip	1519	4.6	6.0
σ		6.4	5.0
Pen	1079	3.9	5.4
σ		4.7	3.9

Figure 9. A Table of average error and dither in grams showing the inherent low accuracy and instability in force application, the relation between 1 and 2 dimensional trials and the improvements afforded by the pen grip.

	Samples	Error	Dither
Subject 1	293	3.0	5.8
Subject 2	587	4.5	6.9
Subject 3	330	15.0	10.6
Subject 4	357	9.9	12.7

Figure 10. A Table showing the range of individual differences in average error and dither force between subjects for the two dimensional tip grip condition

Figure 9 gives the average error and dither under the various conditions. This table shows that even when the data is averaged over all individuals and target forces its major features are still visible. The extremely large standard deviations reflect several features of the data: first that subjects are unable to hold a constant force, second the large variation in accuracy between individuals Figure 10, and third the fact that error and dither increase with increasing force.

The maximum force that subjects seem comfortable applying with one finger is about 8 ounces or 225 grams. Taking this as the working range for finger pressure, average short-term precision can be calculated from Figure 9 The smallest interval of error for the 2 dimensional tip case is 8 grams. Adding the standard deviations to error and dither for the 2 dimensional tip case gives a value of (7.7 + 7.8) + (8.8 + 6.0) = 30 grams as representing an upper range for error. This gives a precision of 3 to 12 percent, allowing 8 to 30 choices in each dimension Figure 9 on page 4. Taking the log base two of these numbers gives an information content ranging from 3 to 4.9 bits for each trial. Averaged over a long hold time (2.4 seconds) subject accuracy came to a precision of 3 to 15 grams, giving 3.9 to 6.2 bits, for each dimension, Taking a long careful attempt, then, only allowed our best subject to be able to accurately select one of 70 force values in each dimension. Compiled into two dimensions this gives a total information content of 7.8 to 12.2 bits.

The general level of information content reported by Schmidt et.al. for arm force [6] (Standard deviation about 10 percent of applied force) is consistent with our results.

The 1 dimensional projection of the 2 dimensional horizontal data results from setting all horizontal components to 0 in the data from 2 dimensional trials. Note that it agrees closely with the data for the one dimensional targets. Data from trials with vertical targets and the corresponding projection of the 2 dimensional trial data are quite similar, with the same close correspondence. The differences in error between 1 and 2 dimensional trials is completely accounted for by the dimension of the trail. The subjects appear to be able to add a second dimension to their task without any interference giving twice the information content without additional effort.

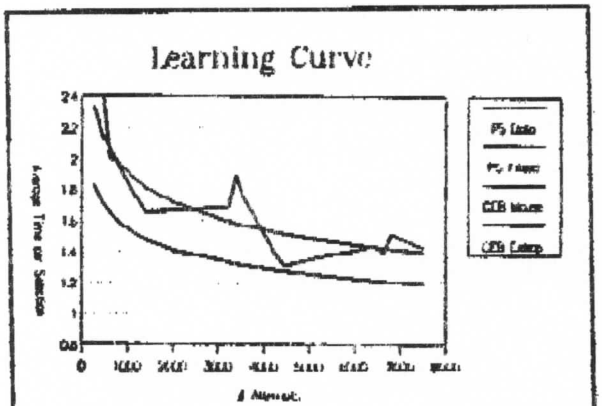

Figure 11. Demonstration of the experience subjects had relative to asymptotic improvement with use of pointing device.

The experiments described in this paper were included in a two day exercise designed to train subjects in using isometric pointing devices for mouse-like selection activities. As with the mouse [1] we find that a subject improves at selection tasks over a few thousand pointing selections. Figure Figure 11shows two points at which Subjects performed these force experiments as part of a longer set of runs designed to give them experience with isometric pointing.

By noting the points along the performance curve at which data was gathered for force experiments, the impact of pointing experience on these results can be estimated. Figure Figure 12 shows that this data is consistent with all other data describing accuracy of finger force.

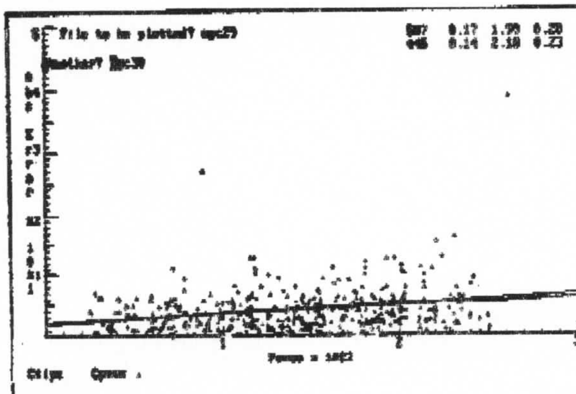

Figure 12. Force accuracy data taken at different times on a user's joystick pointing learning curve.

CONCLUSION

Limits of Digit Force Control

Even under the optimal condition of long integration time, accuracy is quite limited. If we take the working range for this kind of finger pressure as 0 - 225gm, average short-term precision, for our subjects, is in the range of 9 to 25 grams or 4 to 10 percent of full range in each dimension, corresponding to an information content of 3.3 to 4.6 bits for each trial. Over time (2.4 seconds) this is integrated to a precision of 3 to 15 grams, giving 3.9 to 6.2 bits, for each dimension, for a total information content of 7.8 to 12.2 bits. This compares with 18.22 bits represented by the selection of a single pixel on a VGA (640x480) screen. A force-to-position joystick is clearly not adequate as a pointing device. By mapping force into velocity instead of position, efficient time integration and arbitrarily precise pointing may be achieved, provided that the proper mapping is used. The imprecision of finger pressure implies that speed can be closely controlled only where the mapping has a plateau, where the desired speed is maintained over a range of pressures larger than the 4 to 10 percent uncertainty. In the Pointing stick transfer function such plateaus are found at zero speed for a stopped cursor, a slow speed for accurate pixel and character positioning, and at maximum eye tracking speed for fast accurate movements [5] -- Figure id 'transfe' unknown --

Over the range of target forces tested subjects were never able to keep steady forces under 2 grams. A projected average 5 grams of dither at zero force sets a minimum deadband which will allow a user to rest a finger on a sensor without cursor motion.

Two Dimensions is No Harder than One.

Subjects applying a force in two dimensions made much the same errors along each axis as when they were concentrating on that axis alone. One might expect that it would be easier to apply and hold a specified force to the right, for example, if one need not control in the up or down direction. This is not the case.

Role of Grip in Force Control

It might have been expected that the opposing thumb and forefinger hold would greatly improve both accuracy and steadiness of force application. Data from this study shows that the pen grip improved performance very little (Figure 4 on page 3, Figure 9 on page 4). This improvement, however, does not come from the opposing thumb as predicted; a finger placed on the side of the joystick in the side grip condition slightly outperforms the pen grip Figure 8 on page 4shows that the observed force accuracy advantage of the pen grip is due to the finger or thumb position on the side of the sensor rather than on the top, and not to the opposing digits grip. Two unsteady fingers are just as unsteady as one unsteady finger.

Error and Dither are Aligned in the Target Direction

Applied force tends to be aligned to the direction of target force but undershot. For force to velocity transfer functions this is an advantage; the noise along the intended direction of movement changes the cursor speed but not its direction.

A specific style of menu that this suggests is a menu along the edge of a screen (which acts as if infinitely deep).

The results of these experiments help describe behavioral motor issues which contribute to the performance improvements achieved by the Pointing Stick transfer function.

This study shows that individual performance differ by a large factor; could this be taken into account in personalized or adaptive transfer functions?

The noise in a persons movement is greater in the axis directly intersecting the target; could this analysis be utilized to to augment user control?

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