Modeling of Human Hand Force Based Tasks Using Fitts's Law

M. S. Raghu Prasad, Sunny Purswani and M. Manivannan

Abstract Conventional Fitts's model for human movement task finds a common application in modern day interactive computer systems and ergonomics design. According to Fitts's law the time required to rapidly move to a target area is a function of the distance to the target and the size of the target. This paper describes experimental process for prediction of minimum movement time, in a force-variation based human performance task involving right index finger. In this study we have made an attempt to extend the applicability of the conventional Fitts's model for a force based virtual movement task, without taking position into account and evaluate human performance metrics for such tasks. An experiment was conducted in which 6 healthy young adult subject's in the age group of 22–30 years performed force based movement tasks. During each trial, subjects were asked to reach an initial force bar of given thickness W Newtons, corresponding to allowable tolerance. Once the subject's had reached initial level, they were instructed to reach out the target force bar of same thickness W as quickly as possible and bring it back to the initial force level bar, thereby completing 1 iteration. Time required for 10 such iteration was noted for each subject. The results from the experiment show that the relationship between movement time and index of difficulty for force tasks are well described by Fitts's law in visual guided, force-based virtual movement task.

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1 Introduction

Display ergonomics is primarily governed by the Fitts's model [1] involving estimation of movement time involving limb movements over UIs like mouse, joystick, remote controller etc. Generic definition of the Fitts's model is based on the information capacity of the CNS to execute a physical movement task, assisted by the reflection of the same in the virtual environment over a visual display. But, there exist wide variety of modalities involving tasks which present movement in virtual environment but are restricted from significant amount of movements from the user side, and mostly involve accomplishment of the job based on application of a force—torque combination. For example, pressing and pinching task in laparoscopic grasper, z-movement using force-based touch screen etc. Hence, there was a need of establishing a relation for the estimation of movement time for such category of tasks and validate the results over one of the force-based modality.In conventional way, Fitts's law has proved itself effective in predicting movements times involving replication of human limb movements over virtual environments. In this paper we attempt to validate applicability of Fitts's law in force application-based virtual movement task, involving no human movement. In this experiment, the movement amplitude A, for a particular trial task has been replaced by difference in initial and target force, and target width W has been replaced by allowable force tolerance at both initial and target force levels. The procedure is aimed at predicting the minimum movement time, with no allowable delay, which would be set as a base equation for calibrating all sorts of possible force application based movement tasks with variable attributes.

1.1 Fitts's Law

Ergonomics of Human Computer Interface designs have been predominately driven by the Fitts's model of movement time. This model has proven its effectiveness in improving usability of UIs and optimal designing of the size and location of user interface elements. It can also be used to predict the performance of operators using a complex system, assist in allocating tasks to operators, and predict movement times for assembly line work. However it does have some disadvantages, which include un-directional movement prediction and absence of consistent technique of error detection. Various research and comparison studies have evolved around Fitts's model, some of which extend its scope beyond

1-Dimension usability others explore the possible applicability of this movement task based model in different modalities and signal forms. Fitts [1] conducted the reciprocal tapping experiment across various subjects to validate his theory stating—ability to perform a particular movement is directly characterized by the information capacity of brain and is affected by the alternate possibilities of movements. As part of his experiment, subjects were asked to tap two rectangular plates alternately with a stylus. Movement tolerance and amplitude were controlled by fixing the width of the plates and the distance between them. Subjects were instructed to take care of the accuracy by which they perform the movement task rather than speed of reaching the target points. As part of the Fitts's law expression, Index of Difficulty (ID) is specified as the amount of information required to select specific amplitude from the total range of possible movements, and is thus dependant on the amplitude of the movement (A), and the available target size/allowable tolerance to which it must be made (target width W).

$$ID = \log_2\left(\frac{A}{W} + 1\right) \tag{1}$$

Fitts's expression is closely related to the fundamental theorem of communication systems, derived by Shannon [2]. Thus, by varying ID (A and W), IP can be determined by recording MT over the various conditions. Fitts's concluded the invariability of IP over a certain range of values of ID. Using regression analysis, a linear relationship between ID and MT can be established [1, 2].

$$MT = a + b * ID \tag{2}$$

Here **a** and **b** are the information transmission coefficients. In this form, the reciprocal of coefficient b (1/b) is called the index of performance (IP), and its unit is in "bits/sec". The index of performance (IP) indicates how quickly the pointing can be done. The index of difficulty (ID) depends on the width (W) of the target and the distance (A) between the two targets. The difficulty of the task increases when the distance (A) increases or the width (W) decreases. Fitts's law has also been extended to two and three dimension tasks [3–5]. In the field of HCI, Card et al. was the first to apply Fitts' law in computer interfaces [6]. He compared the performances between a joystick and mouse. The results shown by the mouse movement task were comparable values of IP of order of 10 bits/s, to that of the tapping task perform by Fitts'. On the other hand, joystick produced an index of performance value of around 5 bits/s. The usage of Fitts's law reported in the literature [7–10] was based on position alone. After position alone and before our study the following is added. Human performance for pointing and crossing tasks depended on index of difficulty [11] and fitt's law has also been used to effectively predict movement times when steering through constrained paths and spring stiffness control [12, 13]. Our study aims at extending Fitts's law for force based tasks.

Fig. 1 Sitting posture of subject. Platform height was maintained at elbow level, providing least strained shoulder-elbow-wrist position

2 Methods

2.1 Subjects

Six healthy subjects of the IIT Madras community in the age group of 26 ± 4.1 years, weight 69.5 ± 8.36 kg, height 172 ± 5.22 cm, hand length from the index fingertip to the distal crease of the wrist with hand extended 16.9 ± 1 cm; hand width at the MCP level with hand extended 8.1 ± 0.6 cm. All subjects were pre-screened verbally for self-reported handedness, and history of visual, neurological, and/or motor dysfunction. All subjects gave informed consent. No subject was known to have any difficulty in processing proprioceptive estimation. Five Subjects were right handed and one subject was left handed.

2.2 Apparatus

Each subject was comfortably seated on a chair facing a computer monitor and asked to place both of his/her upper limbs on a wooden table positioned at the same height as of the side support of the chair as shown in Fig. 1, thereby maintaining a correct symmetry with respect to the medial axis of the body. The angle made by the index finger with the shoulder joint was approximately 90°. Each subject was instructed to maintain a constant index-finger pressing posture during the course of the experiment. The monitor on which a visual feedback was given was placed 15° below eye level at a distance of 0.6 m away from the participant. A Force Sensitivity Resistors (FSR) of Interlink^{TM} make was used as force sensor.

An FSR for the right hand was mounted on a wooden board such that symmetry was maintained with respect to the hand position. In order to avoid fatigue precautionary care was taken in positioning the FSR in accordance with the participant's right index finger. The display was rendered using Processing 1.5, open source platform, on 160 GB–1.5 GHz, Core 2 Duo PC, running Windows Vista,

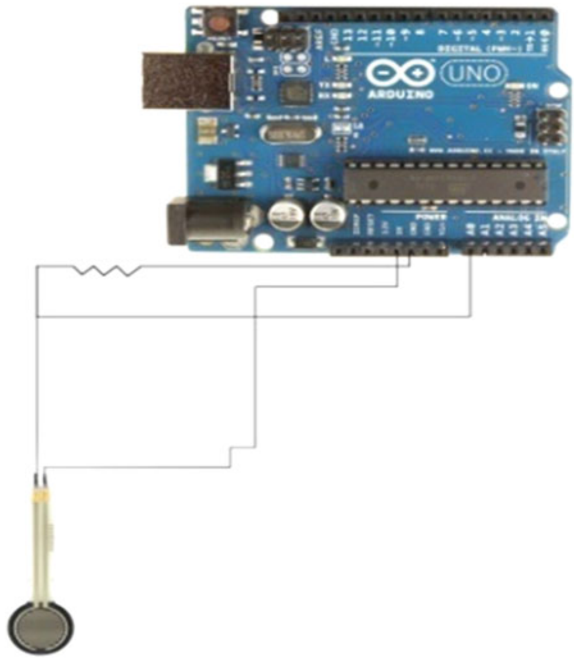

Fig. 2 Circular FSR are connected over a voltage divider circuit with 1,000 Ω loads, under 5 V supply. The input sensor values are triggered into serial port at 100 ms per iteration, with maximum information transmission capacity of 9,600 baud-rate

with 2 GB RAM. The experimental set-up as shown in Fig. 2 comprises of single FSR connected over a parallel voltage divider circuit with 1,000 Ω load under 5 V input supply. The input sensor values were triggered into serial port with a delay of 100 ms per iteration.

2.3 FSR Calibration

The FSR's were calibrated using known weights in the range of 100–1,000 g to obtain the exact values of force applied over the exposed surface of the FSR. A final relation was established between the resistance values of FSR and the applied force, Fig. 3 depicts the calibration graph of the FSR (Table 1).

3 Force Based Fitts's Protocol with Visual Feedback

During each run, subjects were asked to reach an initial force bar of given thickness W, corresponding to allowable tolerance. Once the subject had reached initial level, he was instructed to reach out the target force bar of same thickness W as quickly as possible and bring it back to the initial force level bar, thereby completing one iteration. Each subject was supposed to perform 10 such iterations per trial, where in each trial

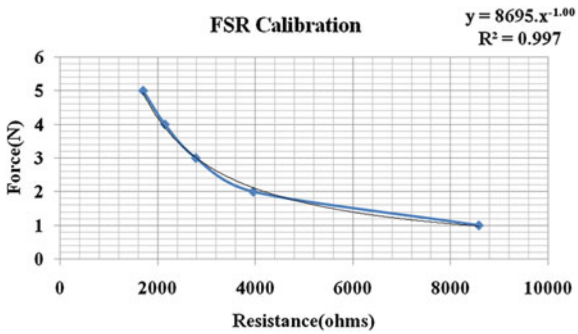

Fig. 3 FSR calibration curve with exponential fit

Table 1 FSR calibration data

Force (N)	Resistance (Ohms)
1	8,578
2	3,957
3	2,781
4	2,147
5	1,700

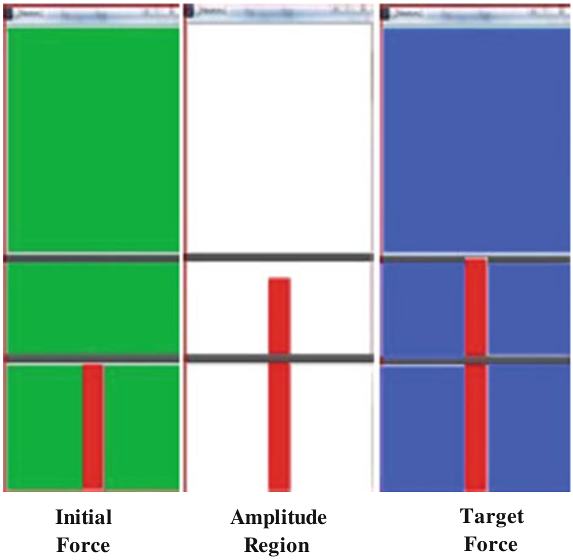

Fig. 4 Visual display

comprised of a unique set of initial force-level, target force level and thickness W. Subject was able to vary the force application by adjusting the pressure exerted by right-index finger over a 0.5″ Circular Force-Sensitive Resistor (Resolution—0.01 N).

Once the subject reached the initial force level, background color of display changed to green as shown in Fig. 4, indicating the attainment of the initial force level. Once the subject pressed over FSR and was able to move to the target force level for given thickness W, background color changed to blue, indicating attainment of target force level and instruction to come back to initial force level. Each subject underwent 50 trials as part of the experiment, force level being pair of combinations out of the (1 , 2 , 3 , 4 , 5 N) set and thickness W being values out of the set of (0.1 , 0.2 , 0.3 , 0.4 , 0.5 N). Each set of values were presented with equal a priori probability, without any bias.

4 Data Analysis

Each trial in subject-wise experiment comprised of 10 iterations, wherein sensor data values were stored at the rate of 10 samples per second. At the end of each trial, average value of all the iterations was calculated, in the following form as shown in Eq. (3).

$$MT_j = \frac{\sum_{i=1}^{10} T_i}{10} \tag{3}$$

MT_j is the average movement time for jth trial and T_i is the time taken by ith iteration. Similarly, average movement times were computed for all the 50 unique trials. Out of 50 MT values, certain set of combinations of A (Difference in force levels) and W (Allowable force tolerance) produced same A/W ration, thereby denoting same Index of Difficulty (ID). Hence, movement time for such sets of values for a given A/W was normalized to their mean.

5 Results and Discussion

Linear regression plot was performed over the final set of Index of Difficulty [ID = Log_2 (A/W + 1)] values against the respective minimum movement times (MTs). R-squared values were evaluated using least-square method for establishing the degree of correlation of the actual values with the corresponding regression plot. Process was repeated across all 6 subjects, individually. A direct

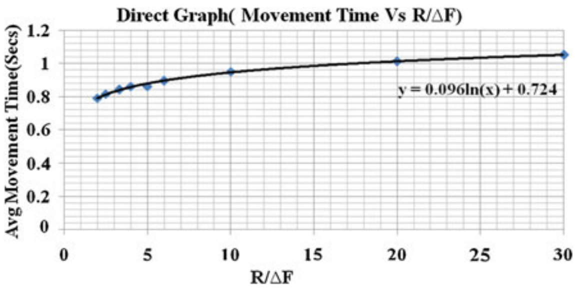

Fig. 5 A logarithmic fit to the data set of movement time and index of performance

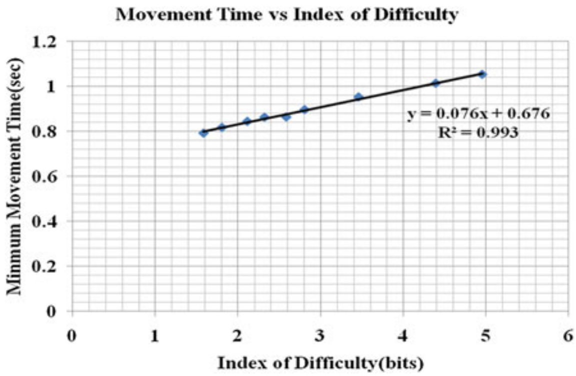

Fig. 6 A linear fit to the data of movement time versus index of difficulty

Table 2 Standard deviation and confidence values of all subjects

R/deltaF	ID	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Avg (MT)	Std Dev	Confidence
2.00	1.58	0.71	0.73	0.89	0.69	0.83	0.90	0.79	0.09	0.08
2.50	1.81	0.75	0.73	0.98	0.72	0.88	0.85	0.82	0.10	0.08
3.33	2.11	0.74	0.73	1.08	0.80	0.87	0.84	0.84	0.13	0.10
4.00	2.32	0.83	0.79	0.73	1.10	0.86	0.86	0.86	0.13	0.10
5.00	2.58	0.93	0.80	0.79	0.89	0.86	0.91	0.86	0.06	0.05
6.00	2.81	1.10	0.69	1.05	0.75	0.79	1.00	0.90	0.17	0.14
10.00	3.46	0.87	0.76	1.18	0.90	1.06	0.94	0.95	0.15	0.12
20.00	4.39	0.96	0.78	1.23	0.91	1.15	1.05	1.01	0.16	0.13
30.00	4.95	1.03	0.79	1.28	0.93	1.20	1.08	1.05	0.18	0.14

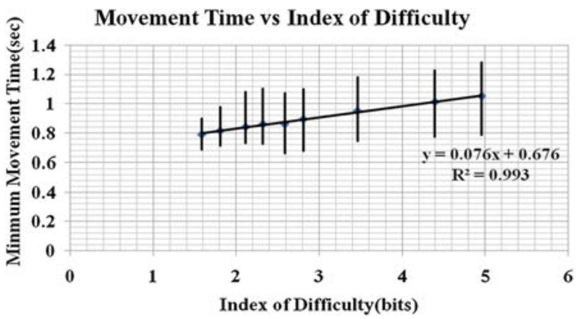

Fig. 7 Plot of movement time and index of difficulty

graph of Movement Time and index of performance is shown in Fig. 5 with a logarithmic fit where R = difference in Force levels and ΔF = allowable tolerance. The slope of the graph represents the performance of the control as for the data with visual feedback. Each subject produced R-squared values of more than 85 % accuracy corresponding to their projected linear regression plots of minimum MT versus ID, thereby validating 1D Fitts's law in force domain. Figure 6 shows the final plot of Movement time (MT) versus Index of Difficulty (ID) averaged across all 6 subjects. Plot presents an R-squared value of 0.993, denoting a very accurate representation of the Fitts's law in static force application based movement tasks over the pre-defined force range. Here final values of constants **a** and **b** are 0.676 and 0.076 respectively.

Table 2 depicts the standard deviation and confidence values across all subjects with the index of performance and index of difficulty. Figure 7 shows the graph of the ratio of difference in force levels to the allowable tolerance plotted over the data set of index of difficulty and movement time. The results indicate that Fitts's law applies to the activities in muscle space, as well as the movement and force in task space. The results from this study infer that Fitts's law applies to the activities in muscle space, as well as the movement and force in task space. This may imply that Fitts's law is determined in the level of the nervous system and is not affected by the dynamics of the limbs. The results strengthen the argument that the trade-off between speed and accuracy of the pointing movement is determined by the capacity of information transfer of the central nervous system (CNS), rather than the physical limitations of the arm, such as inertia and mechanical compliance [8]. Moreover during the course of the experiment, control rate and homing time turned out to be crucial factors in accomplishing the task under variable set of parameters [7, 14–16].

6 Conclusion

In this study we have explored the possibility of using the well established Fitts's model to force based human hand movement tasks. The final derivation of the Fitts' law expression after regression analysis over the generalized data collected across 6 subjects. R-squared value of more than 95 %, justifies the validity of Fitts's law in force-based movements in virtual environments irrespective of involvement of limb movements. The results from the experiment show that the relationship between movement time and index of difficulty are well described by Fitts's law in visual guided, force-based virtual movement task. These results, open up scope for extending this research to establishment of Fitts's law to 3-Dimensional virtual environments (e.g. laparoscopy surgical training platform) involving movements and orientations synchronized by application of multi-directional force and torque. Further the study can be used as a basic foundation in modeling and design of force based minimally invasive surgical training modules in order to assist resident doctors to hone their surgical skills.

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