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TWO MEASURES OF PERFORMANCE IN A PEG-IN-HOLE MANIPULATION TASK WITH FORCE FEEDBACK*

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ABSTRACT

This paper describes the results from two manipulators on a peg-in-hole task, which is part of a continued effort to develop models for human performance with remote manipulators. Task difficulty is varied by changing the diameter of the peg to be inserted in a 50 mm diameter hole. An automatic measuring system records the distance between the tool being held by the manipulator and the receptacle into which it is to be inserted. The data from repeated insertions are processed by computer to determine task times, accumulated distances, and trajectories. Experiments with both the MA-11 cable-connected master-slave manipulator common to hot cell work and the MA-23 servo-controlled manipulator (with and without force feedback) are described. Comparison of these results with previous results of the Ames Manipulator shows that force feedback provides a consistent advantage.

INTRODUCTION

The task investigated in this paper is the peg-in-hole experiment previously examined by McGovern[1] and Hill.[2] The experiment board has been rebuilt to be more precise and to be incorporated into the measuring system. The experiment has been expanded to use three different moving distances (100, 200, and 400 mm) to provide a broader data base for the models.

Two manipulators were chosen for these experiments. The first was the French MA-11, a lightweight cable-connected manipulator designed for hot cell work. Similar to the Model 8 developed at Argonne Labs, it is representative of a large class of manipulators in use throughout the world in radioactive environments. With about 30,000 cable-connected manipulators in use in the world, they provide a standard for comparison with other types of manipulators. They offer the operator a low mass (5 kg) manipulation link to tasks with only six degrees of freedom. This link essentially removes the enormous dexterity and tactile sensibility of the human hand and limits the operator to motion and sensing with the six degrees of freedom provided.

The second manipulator chosen was the MA-23 force reflecting servo manipulator developed by the French Atomic Energy Commission (CEA). This manipulator system may be run with force feedback either turned on or off. It is one of about 20 manipulators in the world with this feature. An attempt was made to run the experiments with a similar American manipulator, the E-4 manipulator at Fermi National Accelerator Laboratory, Batavia, Illinois, but it was not operational at the time scheduled for the experiment. Manipulators with force feedback capability were sought to characterize the changes in performance attributable to force feedback.

The performance measuring system is based on a tensioned string that measures the distance between the tip of a tool and a receptacle into which the tool is to be inserted. The string also permits the progress into the hole to be monitored as the tool is inserted. From records of string length as a function of time, tool trajectories as well as velocities and task times can be determined. The system makes a permanent record of the string length 25 times a second as the tool is moved to and into the receptacle.

PORTABLE DATATAKER

A portable data collection system was designed and constructed to obtain and compare performance of different teleoperators. The system measures the distance from a tool to a receptacle in which the tool is to be inserted. The datataker records the distance between the end of the tool and the bottom of the receptacle as a function of time. This distance is measured by a dacron string of low extensibility to the

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nearest 2 mm and is punched on paper tape at the rate of 23 measurements/sec. The range is calibrated from 0 to 510 mm in 256 steps (8 bits).

The entire experimental arrangement is shown in Figure 1. The experimenter operates the tape perforator, while the subject manipulates

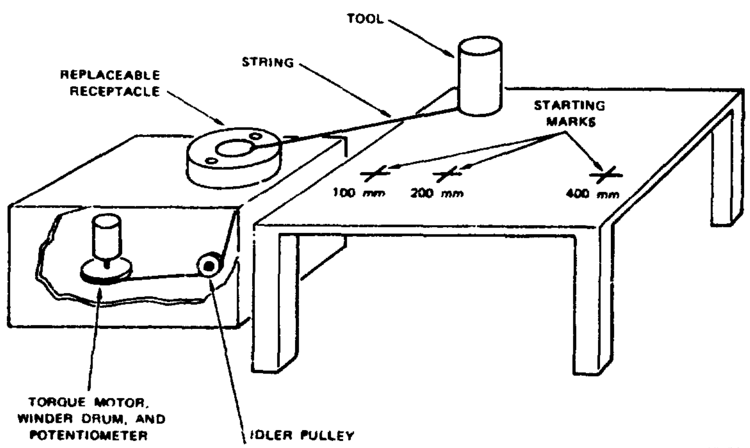

FIGURE 1 TASK CONFIGURATION WITH MEASURING UNIT AND ACCESSORY TABLE

the tool. The measuring string connects the tool and the string puller. This system is similar to that previously described[2] for measuring the X, Y, and Z coordinates of the manipulated tool, except that a single string is used. This simplification in measuring was suggested by the results of two previous studies using a more sophisticated datataker.[1,3] In these studies the distance between hole and tool as a function of time was the most important parameter in explaining the experimental results. This measurement could be used to divide the task into different therbligs and to proportion a fixed amount of time for each one. Detailed descriptions of the equipment including dimensions of the task boards and operation of the datataker are given in a technical report.[4]

A data reduction program reads the paper tapes and makes a set of measurements on the trajectories. The measurements, a sample of which is shown in Figure 2, are briefly described below:

<u>Reaction Time</u>--Reaction time is the time after the experimenter turns on the punch, which is the audible signal for the subject to begin, until the subject pulls the string 4 mm from its initial length (time zero).

<u>Zero Length</u>--Zero length is the string length when the tool is at the entrance to the receptacle. This length is determined from the calibration recordings.

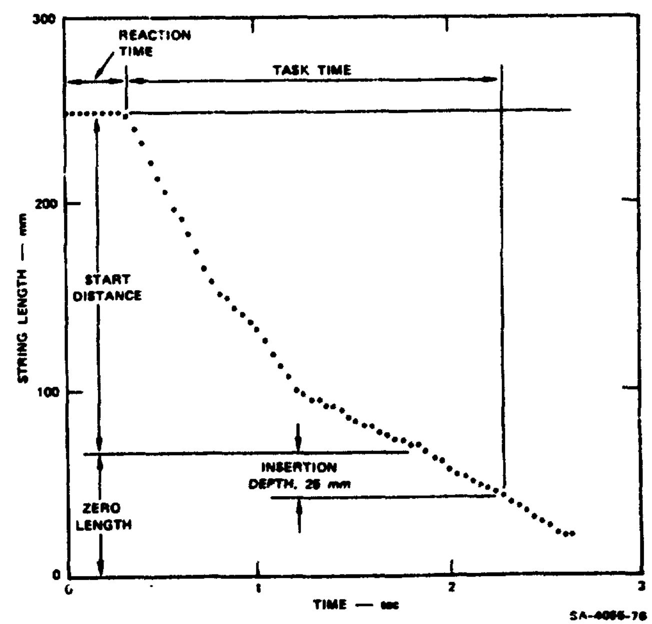

FIGURE 2 SAMPLE TRAJECTORY MEASURED BY DATATAKER

Start Distance--Start distance is the difference between the string distance at time zero and zero length as defined above.

Task Time--Task time is the time from when the tool is first moved until it has been inserted 25 mm into the receptacle.

In addition to these parameters, the first times to a set of given distances from the hole entrance are determined in order to plot the average trajectory. The set of distances are: 350, 300, 250, 200, 150, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, and 0 mm from the hole and 10, 20, 25, and 30 mm into the hole.

PEG-IN-HOLE EXPERIMENT

The object of the task was to insert a set of pegs into a round receptable. The difficulty of the experiment was varied by using pegs of different diameter. The experimental apparatus is basically the same as that used by McGovern.[1] The same pegs were used but a more precise receptacle was installed on the taskboard. Tool trajectories were recorded as a function of time, using the data acquisition system.

Manipulators

Two different manipulators were chosen for use in the experiment: a lightweight master-slave manipulator (MA-11) of the family used for hot cells and a heavy duty servo manipulator (MA-23) that has more general purpose use. These manipulators are shown in Figures 3 and 4. Technical descriptions including dimensions, load capability, speed, and backlash for the MA-11 and MA-23, respectively, are given in a technical report.[4] Both manipulators were developed by the French Atomic Energy Commission at Saclay, France, for radioactive handling by Dr. Jean Vertut's Environmental Protection group.[5,6]

Experimental Design

The basic experiment consists of the 7 × 3 × 3 factorial design shown in Figure 5. For each distance and peg combination, eight insertions of the peg into the receptacle were made. Seven pegs were used (Pegs 2, 4,

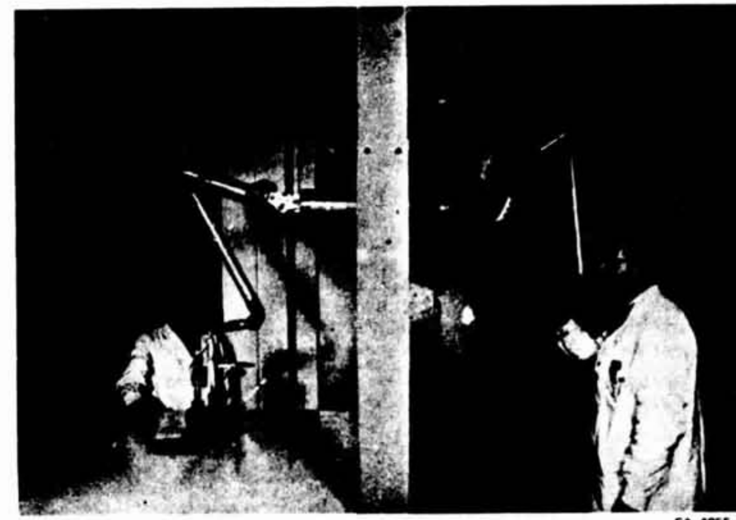

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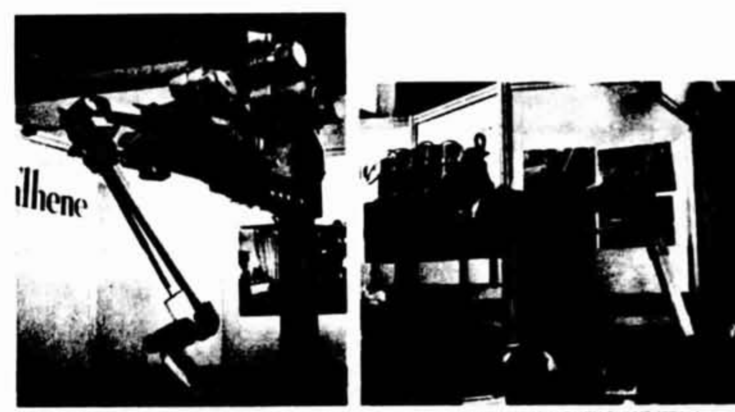
FIGURE 3 MA-11 CABLE-CONNECTED MASTER-SLAVE MANIPULATOR



(a) MA-23 FORCE-REFLECTING MASTER (5 kg) (b) MA-23/200 HEAVY DUTY SLAVE (25 kg)

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FIGURE 4 MA-23 SERVOMANIPULATOR

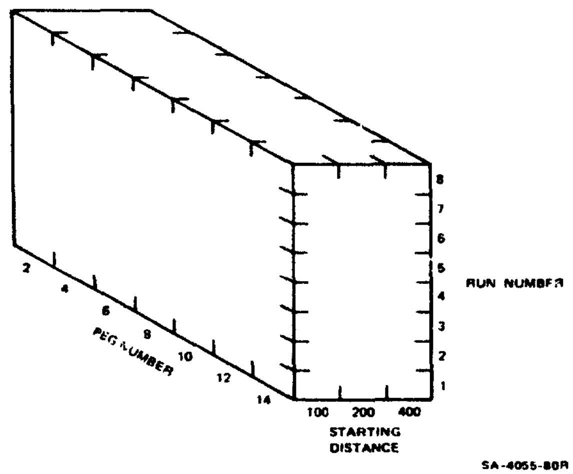

FIGURE 5 PEG-IN-HOLE EXPERIMENTAL DESIGN

6, 8, 10, 12, and 14, which are respectively 25.40, 38.10, 44.45, 47.62, 49.23, 50.39, and 50.70 mm in diameter). The diameter of the hole is 50.40 mm (2.000 inch). This design is similar to that previously used,[2] except that three distances, 100, 200, and 400 mm are used. These distances increase by multiples of two for convenience of using and testing Fitts law.[6]

Procedure

The experimental protocol was as follows: For each sequential condition, a new peg, if called for, was rigidly fixed inside the manipulator jaws by means of a small C-clamp. The subject was permitted to make a few practice movements, and, if a new tool or manipulator were being introduced for the first time, the subject was encouraged to practice a few times. For each of the eight repeated insertions, the subject positioned the tip of the tool over the appropriate starting mark (100, 200, or 400 mm). The experimenter punched the run number, waited a second or two, and switched on the punch, which had a distinct noise. When the subject heard the noise, he proceeded to move the tool into the receptacle. When the tool tip disappeared inside the receptacle (about 50 mm) the experimenter turned off the punch and the subject returned the tool to the starting mark to prepare for the next insertion.

MA-11 RESULTS

The peg-in-hole experiment was run with two subjects in the manner previously described and the resulting trajectories analyzed by computer program to obtain task times and details on the trajectories. Task completion time is defined as the time from the beginning of the move until the tip of the tool is inserted 25 mm into the receptacle. At this point the tool is first inside the 25 mm thick receptacle, and the angular and translational degrees of freedom are constrained as determined by the geometry of the tool and receptacle.

Basic task times for the peg-in-hole task are shown in Figure 6. These times increase as the difficulty of the task (peg number) increases. Differences between the three trajectory lengths appear to be constant, all three increasing with peg number. This suggests that the times are accounted for by the sum of two functions; one a function of trajectory length, the other a function of peg number (difficulty).

Since the precision of fit of each peg is double that of the preceding one, the abscissa on Figure 6 is also a measure of task difficulty as defined by Fitts.[7] An interesting feature of the results is their upward curvature: task time is an accelerating function of difficulty, whereas Fitts law predicts a linear function of difficulty. Analyses of variance were performed on the total task times to obtain the statistics for testing hypotheses about these functions.

Task time is a strong function of the peg number [$F(1,294) = 56.49$, $p < 0.001$] and is nonlinear [$F(4,294) = 12.4$, $p < 0.001$]. Task time is also a strong function of the trajectory length [$F(2,294) = 65.80$, $p < 0.001$] but there is insufficient evidence to show that it is nonlinear [$F(1,294) = 0.05$, $p > 0.05$]. The interaction between peg and trajectory

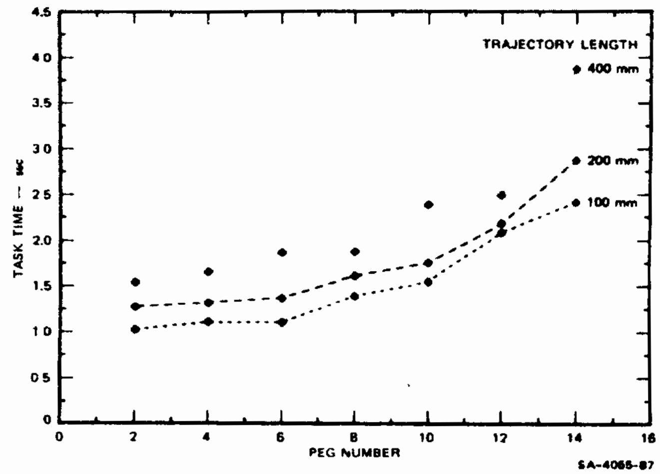

FIGURE 6 MA-11 TASK COMPLETION TIMES

length [$F(12,294) = 1.69$, $p > 0.05$] is not statistically significant, suggesting independence between these two parameters. With this information we can assume the following model for this task:

$$\text{Task time} = f_1(\text{peg}) + K_1(\text{trajectory length}) \quad (1)$$

where f_1 is an accelerating function of the peg number and K_1 is a linear function of trajectory length.

Trajectories for Pegs 2, 8, and 14 are shown in Figure 7. The trajectories show a transition between the smooth insertions with Peg 2 to the two-stage insertion with Peg 14, where the insertion is practically stopped at the entrance to the hole. Similar transitions between smooth and two-stage insertions were observed in previous experiments[1,2] as the task difficulty was increased. Note that the initial trajectories for the three pegs shown in Figure 7 have the same slope even though the scale change makes it appear that Peg 14 is inserted faster.

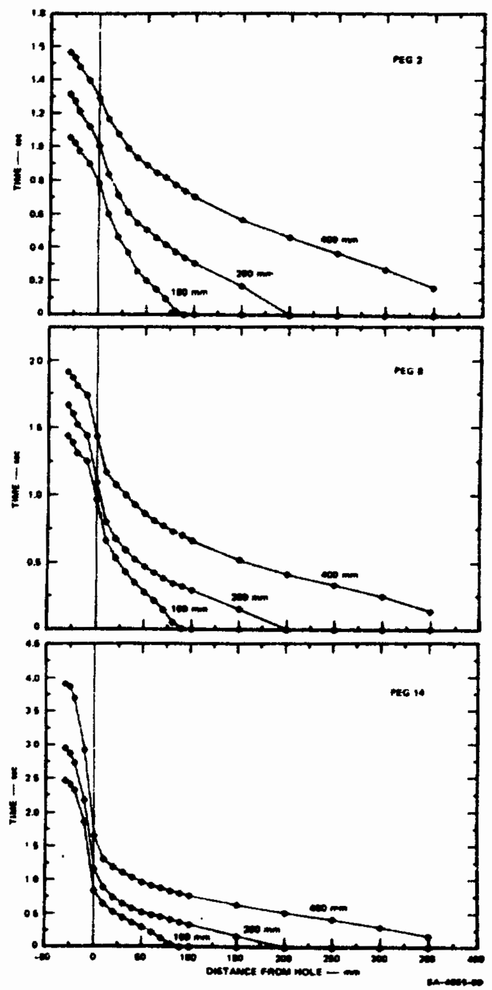

FIGURE 7 MA-11 TRAJECTORIES WITH INCREASINGLY DIFFICULT PEGS

MA-23 RESULTS

In part of a program to determine the advantages of force feedback in different manipulation tasks, the Peg-in-hole task was run on an MA-23 manipulator with and without force feedback. The comparison was made with two subjects who served in both the force and no-force conditions. The experiment was balanced for practice effects by starting one subject on the force and the other on the no-force condition and running the two through the design in reverse directions.

The task times shown in Figure 8 are of the same shape as those of the MA-11. Generally, the MA-23 is 30 to 40% slower without force feedback than with it. There are no distinctive changes as the peg number increases except for the most difficult peg (Peg 14). Here the insertion time is doubled when force feedback is removed.

An analysis of variance of the MA-23 task times shows that times with force feedback are significantly shorter than without it [$F(1,588) = 129$, $p < 0.001$]. Task completion times are also strong functions of the peg and the trajectory length, both being statistically significant at the 0.001 level. Task completion times are nonlinear functions of the peg number, as with the MA-11, because the nonlinear term is statistically significant at the 0.001 level [$F(5,588) = 19.16$, $p < 0.001$]. The nonlinear term in the trajectory length [$F(1,588) = 0.19$, $p > 0.05$] is not significant, indicating that, again, the time is a linear function of trajectory length. Of the three interactions, force feedback and peg number interact significantly ($p < 0.001$), whereas force feedback and trajectory length do not ($p > 0.05$), and peg number and trajectory length do not ($p > 0.05$). These results indicate that there are two models for MA-23 performance in this task. With force feedback we have

$$\text{Task time} = f_f(\text{peg}) + K_2(\text{trajectory length}) \qquad (2)$$

and without force feedback we have

$$\text{Task time} = f_{\bar{f}}(\text{peg}) + K_2(\text{trajectory length}) \qquad (3)$$

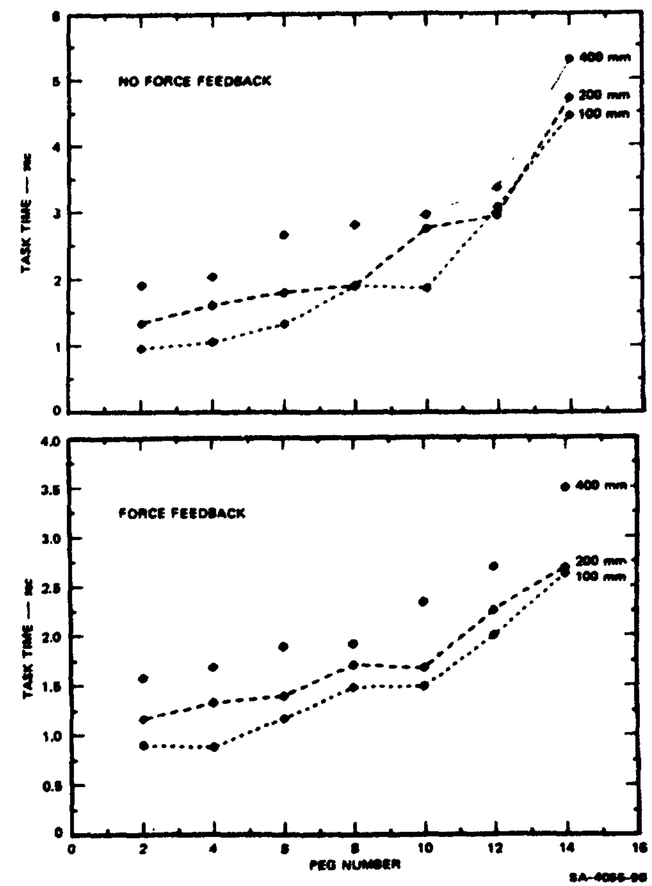

FIGURE 8 COMPARISON OF TASK COMPLETION TIMES WITH AND WITHOUT FORCE FEEDBACK

where the two curving functions, f_f and $f_{\bar{f}}$ of peg size are different, and the linear functions of K_2 of trajectory length are identical.

The trajectories shown in Figure 9 also indicate the general reduction in task time with force feedback. There is a slowing down near the receptacle entrance (between 0 and 10 mm from receptacle) when force feedback is absent, and the insertions take about twice as long without force feedback as with it. The general increase in time without force feedback is apparent throughout the results; gross trajectories as well as fitting movements require more time. With the shortest trajectory (100 mm from the receptacle) gross motion and fitting are intertwined, and it may be impossible to separate these motions (or therbligs) from the data without a model.

SUMMARY

The formulation for the peg-in-hole task with the two manipulators (Equations 1, 2, and 3) shows that task time is a sum of two independent functions--a nonlinear function of peg number and a linear function of trajectory length.

Task times as a function of peg are illustrated in Figure 10 for several situations. Shown are data from the 400-mm trajectories performed with the MA-11 and MA-23 taken from this experiment and data from McGovern[1] (406 mm trajectories) using the Ames Arm and the unaided human hand. The same set of pegs was used in each experiment. Nearly identical functions were obtained under the two force feedback and the two no force feedback conditions, although different manipulators and test subjects were used. Two functions explain the results of all the manipulators: one for force feedback (f_1, from Equation 1, and f_f from Equation 2), the other for no force feedback ($f_{\bar{f}}$ from Equation 3). It thus appears that the task time can be predicted from the geometry of the task (peg number) and the presence or absence of force feedback.

Task times as a function of trajectory length are shown in Figure 11. The linearity of the results as well as the similarity of the two force feedback conditions are obvious for the MA-11 and MA-23 (no force

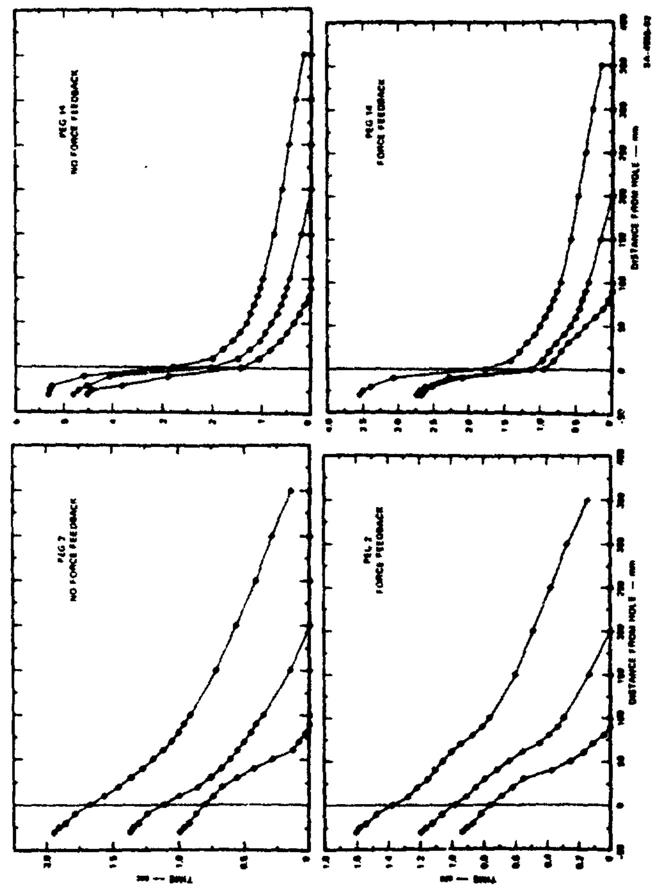

FIGURE 9 COMPARISON OF MA-23 TRAJECTORIES WITH AND WITHOUT FORCE FEEDBACK

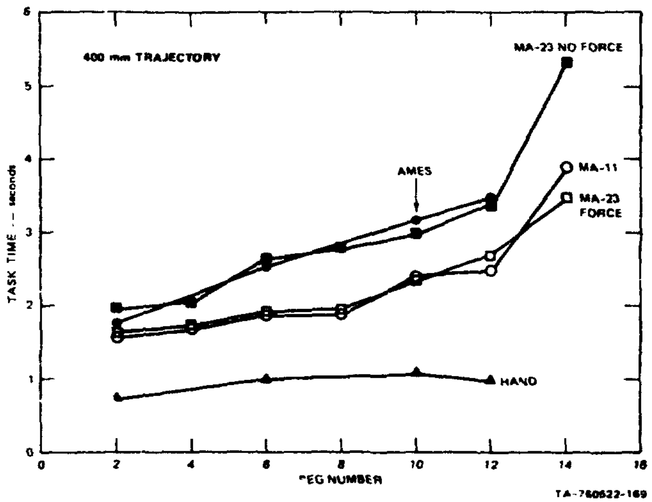

FIGURE 10 TASK TIMES FOR FIVE DIFFERENT PEG-IN-HOLE EXPERIMENTS

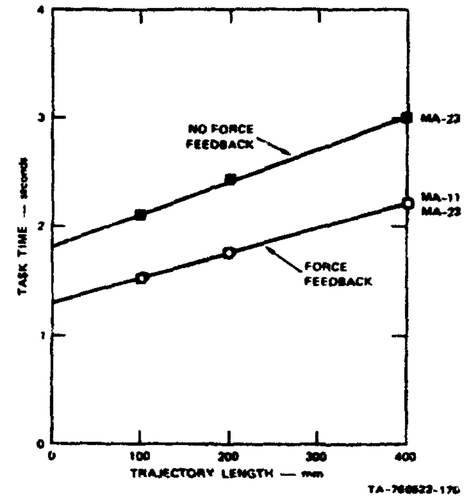

FIGURE 11 AVERAGE TASK TIME VERSUS TRAJECTORY LENGTH

feedback) experiments. A statistical analysis of the results indicates that there is insufficient evidence to show that the slopes of the two lines are different [$F(1,488) = 1.76$, $p > .05$]. This suggests that a common linear function describes the trajectory times of the task for both manipulators (K_1 from Equation 1 equals K_2 from Equations 2 and 3).

In conclusion, the functions for peg number and trajectory length offer a mathematical basis that there are two independent parts of the task, a trajectory part and a fitting part, which substantiate the results of Hill and Matthews[7] with a degree-of-constraint task, and the industrial time-and-motion studies with additive transport and positioning times. These results do not agree with Fitts' Law,[4] which assumes an inverse relation between trajectory length and precision. Thus, the distance moved and the type of force feedback appear to be basic measures of manipulator performance, independent of manipulator.

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