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# Test of Operator Endurance in the Teleoperation of an Anthropomorphic Hand

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**Abstract**

An anthropomorphic hand is a promising end-effector that can use the same interfaces which are designed for humans, and it is often teleoperated using virtual reality tools such as a glove and a helmet-mounted display. In space teleoperation, however, operators need to control robots at a slower speed with more accuracy than on the ground. One of the critical problems is operator fatigue caused by the slow motion and long duration of the operation. In this paper, a comparison experiment between two different operator interfaces, telepresence interface and joystick interface, is described with regard to operator endurance in the space teleoperation of an anthropomorphic hand. Experiment results indicate that the operator's fatigue and sense of difficulty have a correlation with the operation accuracy using the telepresence interface. In addition, most of the test subjects preferred the joystick interface for the specific task, regardless of the operation time. The joystick interface was rated higher for precision, intuitiveness, and comfort, while the telepresence interface was rated higher for flexibility. A combination of different interfaces depending on the tasks is suggested for a practical operator interface.

## 1. Introduction

An anthropomorphic robot is expected to offer a promising solution to conduct operations in the hazards of the space environment as both an astronaut assistant and, in some situations, as an astronaut surrogate. Its anthropomorphic hands would especially allow the robot to use the same interfaces that are designed for humans.

When remotely controlling an anthropomorphic robot or hand, virtual reality tools such as a glove, helmet-mounted display, and wrist sensor are used, since a master-slave pairing is a good way to control a large number of degrees of freedom simultaneously. This type of interface, fully immersing the operator in the robot's workspace and creating a sense of 'presence' at the robot worksite, is usually called a telepresence interface. A telepresence interface is considered to excel in realizing intuitive operability. This is especially true when a person performs at the same speed and accuracy as in daily life.

In space teleoperation, however, operators need to perform more cautiously in order to make no mistakes at a considerably lower speed than that in daily life, and the difference in speed and precision may reduce the effect of the telepresence approach, especially in a long operation. When teleoperating from the ground with a wrist sensor for a hand position, for example, it can be fatiguing and stressful for the operator to keep lifting his/her arm during slow tasks without a pause. It may also be difficult for the operator to make no unnecessary moves like scratching his/her head in a long operation.

One solution could be to divide the tasks into small pieces and conduct them step by step with a pause between the steps. In a real situation, however, the operator needs to get out of immersion in order to rest, since most of the time the slave robot needs to remain in the same position and posture. If the operator needs frequent rests during a long and critical operation, periodically repeating the process of immersion, including a sort of mental calibration, would not be efficient.

In designing an operator interface, it is important to take operator endurance into account, especially for tasks that last a long time. As traditional input devices such as joysticks excel in precise and slow manipulation, we assume that the traditional input devices will be able to reinforce virtual reality tools even for an anthropomorphic hand operation. Especially for the tasks that are relatively easy for making numerical models of the workplace, it would be easy to install an effective operator aide.

Our point is not to replace the telepresence interface with other interfaces, but to support it by combining other interfaces depending on the tasks.

In positioning a whole anthropomorphic robot, for example, it would be better to use a telepresence interface to control tens of degrees of freedom simultaneously, but in a time-consuming, precise manipulation, the use of another interface would be better, concidering the hand as an end-effector, not as a human-like hand. If an anthropomorphic robot needs to handle a wide variety of tasks, it is natural that the operator would also be supported in various ways according to the tasks.

We conducted a user interface experiment using NASA's Johnson Space Center's anthropomorphic robot, Robonaut, to investigate different operator interfaces with regard to operator endurance. In this paper, the two operator interfaces, telepresence interface and joystick interface, are compared using objective data and a subjective evaluation.

**2. Related Research**

The development of an anthropomorphic hand was originally initiated as an approach to find a general-purpose end effector that could perform a variety of tasks efficiently. The concept of an anthropomorphic hand with four or five fingers was first introduced to achieve dexterity by alternating the fingers used to grasp so as to achieve richer manipulation patterns, though kinematically optimized hands are not anthropomorphic [1]. The study of a human-like hand progressed when advanced research tools such as the Utah/MIT Dexterous Hand [2] became available in 1980s.

Concerning operator interface in teleoperation, anthropomorphic hands are usually operated with virtual reality tools such as a glove, helmet-mounted display, and wrist sensor, since a master-slave pairing is a promising way to control a large number of degrees of freedom (DOF) when regarding the hand as a human hand rather than as a robotic end effector. This is partly because virtual reality tools, such as the Data Glove, became available in the same period, in the 1980s, as computer technology greatly progressed [3].

There are several anthropomorphic hands in the world that are designed mainly for space application. Three of them are introduced here. Robonaut is NASA's anthropomorphic robot and is the first humanoid built for space at NASA's Johnson Space Center [4]. Its dexterous hand has five fingers and a total of 12-DOF, and it is designed to have EVA compatibility by reproducing the size, kinematics, and strength of the space-suited astronaut's hand. Robonaut's primary mode of operation is through a telepresence control system, using virtual reality gloves and a helmet. The DLR Hand is a four-fingered robot hand with a semi-anthropomorphic design, consisting of four identical fingers [8,9]. Its goal is to integrate all actuators in the hand's palm or in the fingers directly. The hand is controlled by a Data Glove and a tracker. The hand developed at the National Aerospace Laboratory of Japan is being developed as a general-purpose hand, presently consisting of three fingers [10]. It is currently controlled mainly by a program, and a teleoperation system is being developed.

**3. Robonaut and Selected Interfaces**

The slave manipulator, Robonaut, is an anthropomorphic robot being developed at NASA's Johnson Space Center as a potential astronaut assistant [4,5]. It has a head equipped with two color stereo vision cameras, an articulated neck, two 7-DOF arms, each with a five-fingered 12-DOF dexterous hand, and a 3-DOF waist. For the experiment, only the right arm and hand were utilized.

The primary user interface for Robonaut is a telepresence interface. The operator is seated in a remote location wearing a Kaiser Electro Optics, Inc. (Carlsbad, CA) ProView 60 helmet-mounted display (HMD) through which he/she sees what the robot sees, a Virtual Technologies, Inc. (Palo Alto, CA) Cyber Glove on the right hand that measures the displacement and bending of the fingers, and a Polhemus FASTRAK ® (Colchester, VT) sensor on the wrist that measures the position of the operator's hand relative to a fixed transmitter. Figure 1 (a) shows a subject seated wearing the telepresence hardware.

Our hypothesis was that the telepresence interface would excel for short-time operations but would get less effective with regard to operator endurance as the operation time increased because it could be tiring and stressful for the operator to keep lifting his/her arm during slow tasks without a pause, while at the same time, wearing an HMD and watching the stereo display. We chose another interface to be compared to the telepresence interface and conducted a comparison experiment to verify this hypothesis.

There were many options in selecting a comparison interface, but we focused on replacing the wrist sensor and the HMD of the telepresence interface, since the main sources of fatigue are considered to be the eyes and the arm. We also set the below criteria to construct a comparison interface.

・Input device suitable for space operation

Assuming space operation, an input device should be suitable for a precise and slow operation.

For this experiment, a joystick was chosen for commanding the wrist position because it was considered better for precision and operator comfort in space teleoperation than other devices, such as a master arm or space mouse [6]. In addition, a joystick is currently the most common input device on manned systems.

・Least use of visual information

Visual information is a very effective way to convey precise information. However, since continually watching changing visual cues can easily lead to fatigue and disturb the operator in a longer operation, we adopted a force-reflection approach using virtual constraint to convey information [7]. The operator watched either of the Robonaut's eye views monocularly on a flat display. Other information, such as the workplace model, was conveyed to the operator via force-reflection. Thus, the depth information of the HMD was replaced with the joystick force information based on the design value of the work place.

For finger information, the Cyber Glove was used for the joystick interface, too. One-arm operation was assumed for this comparison experiment.

With the joystick interface, the operator is seated in front of a flat display wearing a Cyber Glove on the right hand and commanding the wrist position with the left hand using an Immersion Corporation Impulse Engine 2000 force-reflection joystick. Figure 1 (b) shows a subject using the joystick interface.

(a) Telepresence (b) Joystick

Figure 1 Selected Interfaces

## 4. Experiment Description

A protocol was developed which tests objective precision and subjective fatigue level. It was assumed that objective precision would be affected by the operator's fatigue. Objective precision was defined as the mean absolute distance between the commanded trajectory and the real trajectory, and subjective fatigue was evaluated by a post-test subjective questionnaire. In the hypothesis, it was also assumed that there could be some correlation between objective precision and subjective fatigue.

Crank rotation by the right hand was selected as an experimental task. A 10-cm crank with a handle was placed in front of Robonaut in a position hanging from above and rotated in the horizontal plane (Figure 2).

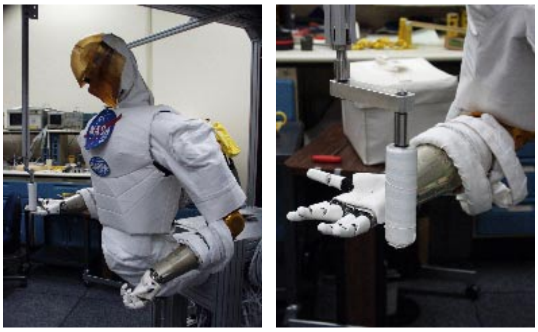

Figure 2 Robonaut and the Crank

A total of eight right-handed test subjects (Subject A through H) participated in the experiment. Six of the eight test subjects had no prior experience teleoperating Robonaut and two of them, A and C, had minimal experience. Five of them had no force-feedback joystick experience and three had some. This experiment aimed mainly at evaluating non-expert performance.

Each test subject conducted two sessions of the crank-rotation task with both the telepresence and joystick interfaces. The task consisted of one trial crank rotation that was comprised of four parts: approach, grasp, rotation, and retreat to the initial position (Table 1). One test session was 30 minutes long with a one-minute break set between the trials for robot hardware safety. Each test subject conducted both test sessions in one day. Half of the test subjects started with the telepresence interface, and the other half started with the joystick interface to remove the test order as a parameter.

Table 1 Crank-rotation Task Definition

| | Action | Operation Type |
|---|---|---|
| 1 | Approach | Free |
| 2 | Grasp | Constrained |
| 3 | Rotate | Constrained |
| 4 | Retreat | Free |

Training sessions were conducted before each test session. Test subjects were introduced to the specific interface and given the task instructions. For both interfaces, the test subjects were instructed to try to operate as precisely and quickly as possible, with more emphasis on precision than on speed. Before each training session, a glove calibration was conducted for each person, and prior to the training session for the joystick interface, a joystick force calibration was conducted to ensure that each test subject felt the appropriate force for the same precision. The training session continued until each test subject felt confident with the interface.

The test subjects were instructed to hold the handle firmly from below by lifting the hand enough for the palm to contact the bottom of the handle, but not to hold the handle only with the fingers. They were also instructed to perform each part of the task sequentially.


Figure 3 Typical View for HMD and Flat Display

Figure 3 shows a typical view for both interfaces. The crank position was a little to the right of the front of the robot and therefore, was not in accordance with the eye direction. Quasi force control was implemented based on the arm joint angle error. Neither interface used direct force feedback. The handle was covered with foam to avoid unnecessary damage to the robot hand.

A second display for the joystick interface in Figure 1 (b) was used for the task instruction in the training session using a graphics simulator, but used only for confirming a joystick mode change, if necessary, during the test session.

For the joystick interface, test subjects were instructed on how to follow the guide force, which showed them the shortest path to the crank handle and the crank rotation path. The workplace model was not too accurate as in the case of modeling the space structure, and the guiding force was set low enough to allow the operator to override the wrong information. With the two-degree-of-freedom joystick, the motion was restricted in two modes, the horizontal plane and vertical plane, but the operator was free to change to either mode and move in any direction.

For the test session, sixteen data files (two for each of the eight test subjects) logging telemetry position, command position, force, torque, and system status were collected. A post-test subjective questionnaire was administered after each session to each of the eight test subjects.

## 5. Results

### 5.1 Objective Results

A statistical analysis considering maximum forces and torques, variance, completion time, cumulative forces, and mean absolute distance between and across all test subjects was performed. Results from this analysis, including individual results, are shown in Table 2. The percent reduction means the reduction of each parameter for the joystick interface over the telepresence interface.

In general, test subjects' performances with the telepresence interface varied widely, while performances with the joystick interface were almost uniform. The dispersion with the telepresence interface did not clearly depend on prior general telemanipulation experience.

#### 5.1.1 Average Maximum Force and Torque

Figure 4 graphs the average maximum force and torque as well as the cumulative force and torque measured across all test subjects.

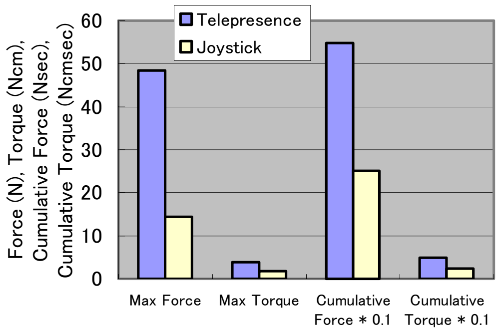


Figure 4 Average Maximum Force and Torque and Cumulative Force and Torque

A reduction in the force and torque was observed for the joystick interface, with an average reduction of 70% for the average force and 55% for the average torque.

Table 2 shows the statistical variance of all these four indexes between and over all test subjects. It indicates a noticeable advantage of test subject performance consistency with the joystick interface. The variances obtained by the telepresence interface are more than ten times higher than those of the joystick interface.

#### 5.1.2 Completion Time

Completion times are compared in Figure 5. The total operation time means the average time for one trial of the operation, and the crank rotation time means the average time used for the crank rotation within the operation.

It is noted that the total operation time was shorter with the telepresence interface, but the crank rotation time was shorter with the joystick interface. It means that the approaching, grasping and retreating tasks took 70 percent of the total time for the joystick interface and 41 percent for the telepresence interface.

Table 2 Performance Analysis Results

| | | Telepresence | Joystick | % Reduction | Variance for Telepres-ence | Variance for Joystick |
|---|---|---|---|---|---|---|
| Number of Total Trials (Number of Retried or Loosely-grasped Trials) | A | 19(0) | 16(0) | | | |
| | B | 16(1) | 17(0) | | | |
| | C | 18(3) | 16(0) | | | |
| | D | 17(2) | 14(0) | | | |
| | E | 15(0) | 14(0) | | | |
| | F | 12(2) | 12(0) | | | |
| | G | 21(1) | 15(0) | | | |
| | H | 20(0) | 15(0) | | | |
| | Avg | 17.3 | 14.9 | | | |
| Average Max Force (N) (Variance (N^2)) | A | 28.2 | 12.4 | 56.0 | 140.4 | 4.8 |
| | B | 50.5 | 14.3 | 71.8 | 271.3 | 9.1 |
| | C | 45.4 | 14.8 | 67.4 | 542.9 | 16.6 |
| | D | 41.9 | 14.7 | 64.8 | 583.7 | 8.4 |
| | E | 27.5 | 12.7 | 53.8 | 84.8 | 3.6 |
| | F | 116.4 | 12.0 | 89.7 | 2511.0 | 5.2 |
| | G | 61.1 | 17.1 | 72.0 | 1826.7 | 110.5 |
| | H | 16.7 | 16.8 | −0.4 | 60.8 | 42.3 |
| | Avg | 48.5 | 14.4 | 70.4 | 752.7 | 25.0 |
| Avg Max Torque (Ncm) (Variance (Ncm^2) | A | 2.4 | 1.8 | 25.5 | 1.2 | 0.5 |
| | B | 5.4 | 1.5 | 72.0 | 6.1 | 0.2 |
| | C | 4.5 | 2.5 | 43.9 | 2.6 | 0.3 |
| | D | 2.7 | 1.5 | 43.4 | 1.8 | 0.1 |
| | E | 1.6 | 1.9 | −21.5 | 0.01 | 0.2 |
| | F | 9.0 | 1.6 | 82.6 | 19.9 | 0.1 |
| | G | 4.3 | 1.7 | 61.2 | 6.2 | 0.3 |
| | H | 1.6 | 1.8 | −15.5 | 0.4 | 0.3 |
| | Avg | 3.9 | 1.8 | 54.5 | 3.2 | 0.2 |
| Cumulative Force (N･sec) (Variance (N･sec^2)) | A | 239 | 174 | 27.2 | 13617 | 720 |
| | B | 728 | 212 | 70.8 | 81067 | 2512 |
| | C | 568 | 259 | 54.4 | 30125 | 5607 |
| | D | 525 | 278 | 47.0 | 60838 | 8906 |
| | E | 403 | 245 | 39.1 | 53977 | 3982 |
| | F | 1277 | 281 | 78.0 | 332489 | 15377 |
| | G | 429 | 236 | 45.1 | 39099 | 3865 |
| | H | 208 | 324 | −55.8 | 7726 | 8682 |
| | Avg | 547 | 251 | 54.1 | 57373 | 5414 |
| Cumulative Torque (Ncm･sec) (Variance (Ncm･sec^2) | A | 22.7 | 21.9 | 3.5 | 183 | 7 |
| | B | 64.3 | 21.8 | 66.1 | 677 | 17 |
| | C | 63.2 | 31.0 | 51.0 | 314 | 25 |
| | D | 39.3 | 23.7 | 39.8 | 195 | 45 |
| | E | 31.9 | 22.0 | 31.0 | 171 | 25 |
| | F | 115.1 | 23.6 | 79.5 | 3194 | 52 |
| | G | 35.8 | 18.7 | 47.9 | 151 | 20 |
| | H | 20.6 | 23.6 | −14.7 | 97 | 44 |
| | Avg | 49.1 | 23.3 | 52.6 | 415 | 27 |
| Total operation time (sec) (Variance (sec^2)) | A | 30.6 | 65.2 | −112.9 | 4.6 | 8.9 |
| | B | 55.3 | 59.5 | −7.6 | 8.4 | 12.5 |
| | C | 54.4 | 62.7 | −15.4 | 4.7 | 10.1 |
| | D | 52.3 | 65.1 | −24.4 | 9 | 11.4 |
| | E | 65.2 | 76.5 | −17.4 | 25.8 | 19.2 |
| | F | 81.6 | 79.9 | 2.1 | 25.9 | 15.6 |
| | G | 39.0 | 57.9 | −48.8 | 5.1 | 10.2 |
| | H | 39.8 | 70.5 | −77.0 | 13.7 | 16.9 |
| | Avg | 52.3 | 67.2 | −28.5 | 12.2 | 13.1 |
| Crank-rotation Completion Time (sec) (Variance (sec^2)) | A | 15.3 | 20.7 | −35.1 | 4.5 | 2.4 |
| | B | 23.7 | 21.1 | 11.3 | 3.1 | 5.1 |
| | C | 31.0 | 22.6 | 26.9 | 3.5 | 3.8 |
| | D | 36.9 | 22.1 | 40.0 | 9.3 | 4.4 |
| | E | 37.3 | 29.1 | 21.8 | 22.0 | 7.0 |
| | F | 55.4 | 28.8 | 48.0 | 24.3 | 5.5 |
| | G | 22.1 | 22.2 | −0.3 | 2.9 | 5.4 |
| | H | 23.8 | 29.2 | −22.5 | 8.3 | 7.4 |
| | Avg | 30.7 | 24.5 | 20.2 | 9.7 | 5.1 |
| Vertical Position Error (cm) (Variance (cm^2)) | A | 1.03 | 0.21 | 79.3 | 1.62 | 0.06 |
| | B | 2.44 | 0.14 | 94.1 | 1.21 | 0.01 |
| | C | 1.82 | 0.48 | 73.3 | 1.28 | 0.16 |
| | D | 2.16 | 0.33 | 85.0 | 1.35 | 0.002 |
| | E | 1.43 | 0.13 | 90.9 | 0.58 | 0.004 |
| | F | 0.14 | 0.19 | −37.8 | 0.67 | 0.003 |
| | G | 0.53 | 0.37 | 30.3 | 0.91 | 0.12 |
| | H | 3.89 | 0.71 | 81.7 | 0.59 | 0.85 |
| | Avg | 1.68 | 0.32 | 80.9 | 1.03 | 0.15 |
| Mean Absolute Distance (cm) (Variance (cm^2)) | A | 2.65 | 0.72 | 73.0 | 0.42 | 0.04 |
| | B | 4.41 | 0.87 | 80.4 | 0.63 | 0.03 |
| | C | 3.68 | 0.52 | 85.8 | 0.36 | 0.12 |
| | D | 4.28 | 0.66 | 84.5 | 0.38 | 0.04 |
| | E | 2.79 | 0.84 | 69.9 | 0.25 | 0.07 |
| | F | 3.56 | 0.57 | 84.0 | 0.51 | 0.24 |
| | G | 2.40 | 0.81 | 66.2 | 0.55 | 0.14 |
| | H | 4.81 | 1.10 | 77.1 | 0.73 | 0.59 |
| | Avg | 3.57 | 0.76 | 78.7 | 0.48 | 0.16 |

This shows that the constraint-involved operation of the crank rotation was done faster with the joystick interface, while the constraint-free operation was done faster with the telepresence interface. In the constraint-free operation, the telepresence interface had the advantage to allow the operator to perform based on his/her natural perception of the world, while with the joystick interface, the operator needed to feel for the position of the objects by gradually tracing the force information.

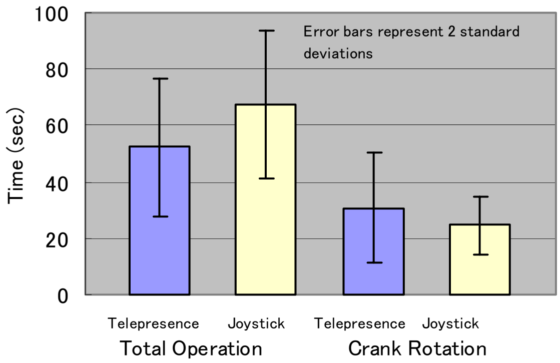


Figure 5 Average Completion Time

### 5.1.3 Mean Absolute Distance

Figure 6 is the graphs of the mean absolute distance measured between and across all test subjects. The mean absolute distance was calculated based on the difference between the commanded trajectory and the real trajectory. In this experiment, this value was defined as an index for the precision of the operation.

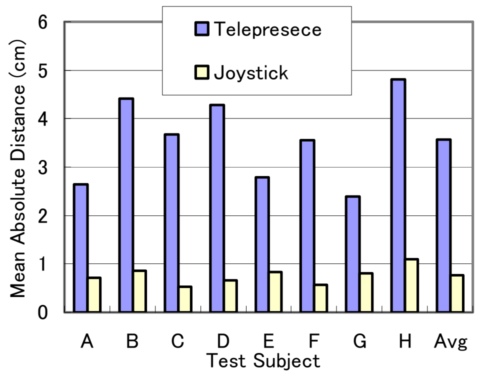


Figure 6 Mean Absolute Distance

A reduction of the mean absolute distance was observed for the joystick interface, with a 79 % reduction on the average. Though this figure shows that there was less error between the commanded trajectory and the real trajectory with the joystick interface, this does not necessarily means that the operation was imprecise with the telepresence interface. That is because most of the operators tried slightly different types of grasping thanks to the hand's flexibility, although they were instructed to use the same grasping method with the palm firmly contacting the end of the handle.

Whether the operators had a firm grasp or not was indicated by the vertical error of the hand position with respect to the end of the crank handle.

Figure 7 shows the vertical error for each test subject and across the test subjects. A one-centimeter error means that the hand was placed one centimeter down from the ideal grasping point. From the experimental analysis, if the hand was within two to three centimeters from the end of the handle, the operator was able to keep his/her grasp most of the time.

Figure 7 shows that all the test subjects except test subject H operated within this vertical limit. Only test subject H's hand position was apparently out of this range. It was observed during the experiment that test subject H pulled down the surrounding foam and rotated the crank only by grasping the foam, not by correctly grasping the handle. This shows that test subject H did not get correct depth information, although test subject H claimed to have had good depth information and actually performed well in the training session as well as at the beginning of the test session. It is noted that this clear inconsistency between the subjective depth perception and the objective data was observed only for this test subject.

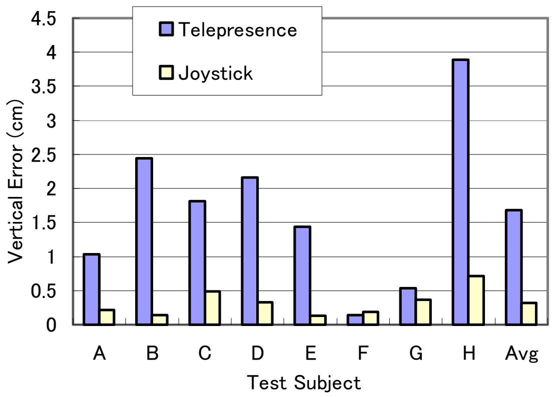


Figure 7 Average Vertical Position Error

The objective performance in general was better with the joystick interface for this particular task. This result was relatively foreseeable, but the performance was even better than expected.

One explanation could be the accuracy of the numerical model used in the joystick interface. If the numerical model were perfect, the joystick force could guide the operator perfectly. For this experiment, however, very high accuracy could not be achieved in the modeling due to some experimental settings, especially due to the fact that the world coordinate was fixed in the robot's movable chest. The crank model was placed in the workplace model based on the hand coordinate when the hand was placed in the grasping position, and the modeling error was about 1 to 2 cm on the average. In addition, the force level was set low so as not to prevent the operator from ignoring or overwriting the force information. Thus, the better performances with the joystick interface may not be explained just by a precise numerical model.

Another explanation would be that the operator had more freedom to correct the command with the joystick interface. Since the operators did not need to keep lifting their right arms, they were able to concentrate more on subtle inconsistencies, such as the one between the deflection of the crank's supporting bar and the force information, and tried to adjust their command. Several test subjects mentioned in their questionnaires that they used these small inconsistencies for command correction.

### 5.2 Subjective Results

In the questionnaires, the test subjects were asked about their subjective fatigue level, task difficulty, and their preference for the interfaces.

#### 5.2.1 Fatigue and Difficulty

Table 3 shows the subjective evaluation of fatigue and difficulty. The test subjects were asked to choose from five levels, with the higher number suggesting greater fatigue or difficulty.

Table 3. Subjective Evaluation of Fatigue and Difficulty (1:Low, 5:High)

| | | A | B | C | D | E | F | G | H | No. of Sign |
|---|---|---|---|---|---|---|---|---|---|---|
| HMD or display fatigue | T | 2 | 1 | 3 | 4 | 1 | 1 | 1 | 1 | 1 |
| | J | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 |
| | ⊿ | -1 | 1 | -2 | -3 | 0 | 0 | 0 | 0 | --- |
| Glove fatigue | T | 2 | 4 | 2 | 2 | 1 | 3 | 1 | 2 | 1 |
| | J | 2 | 3 | 2 | 1 | 2 | 2 | 1 | 1 | 4 |
| | ⊿ | 0 | -1 | 0 | -1 | 1 | -1 | 0 | -1 | --- |
| Overall task difficulty | T | 2 | 2 | 5 | 3 | 5 | 3 | 2 | 1 | 1 |
| | J | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 6 |
| | ⊿ | 0 | -1 | -4 | -1 | -3 | -1 | -1 | 1 | --- |

(T:Telepresence, J:Joystick, ⊿:difference)

A simple sign test using the difference (⊿) between the rates for each interface was done for each test subject. A minus value indicates that the telepresence interface was rated higher and a plus value indicates that the joystick interface was rated higher. The number of signs for each was counted, and a higher number shows a favorable result.

The fatigue level was slightly higher for the telepresence interface than for the joystick interface, although three to four test subjects rated the interfaces equal as far as fatigue . Glove fatigue was somewhat greater than HMD or display fatigue for both interfaces.

The overall task difficulty for the telepresence interface was rated higher than that for the joystick interface by all except two test subjects.

#### 5.2.2 Preference for an Interface

The test subjects were also asked about their preference for the two interfaces with the option of choosing either of them or “no difference” in comparison questions.

Table 4 Test Subjects’ Preference for an Interface (1) (Number of test subjects who preferred an interface, depending on the index)

| Index | Comf-ort | Precisi-on | Intuitiv-eness | Flexib-ility |
|---|---|---|---|---|
| Telepresence | 1 | 2 | 1 | 7 |
| Joystick | 5 | 6 | 7 | 1 |
| No Difference | 2 | 0 | 0 | 0 |

The joystick interface was rated higher for precision, intuitiveness, and comfort, while the telepresence interface was rated higher for flexibility. Contrary to our hypothesis, intuitiveness was associated more with the joystick interface because most of the test subjects interpreted intuitiveness as needing less training time.

Table 5 Test Subjects’ Preference for an Interface (2) (Number of test subjects who preferred an interface, depending on the operation time)

| Operation time | Short (~10min) | Long (~1 hour) | Very Long (several hours) |
|---|---|---|---|
| Telepresence | 1 | 2 | 0 |
| Joystick | 6 | 6 | 8 |
| No Difference | 1 | 0 | 0 |

Table 5 shows the interface preference of the test subjects, depending on the length of the operation time. Again contrary to our assumption, six of the eight test subjects preferred the joystick interface even for a short operation, mostly because of the ease of the operation, according to their comments. For about a one-hour operation, six of them preferred the joystick interface, mostly because of less fatigue. For a several-hour operation, all the test subjects preferred the joystick interface. Two reasons were given by the two test subjects who preferred the telepresence interface for a one-hour operation and preferred the joystick interface for a several-hour operation. One was fatigue due to holding up one arm and the other was the inability to do little things like scratching his/her head or sneezing.

Only one subject found the joystick interface unnatural for the manipulation of an anthropomorphic hand, and two test subjects mentioned that they would like to use both interfaces combined.

### 5.3 Comparison between Objective and Subjective Results

One of our hypotheses was that the operator’s fatigue would affect the precision of the operation more with the telepresence interface than with the joystick interface. The mean absolute distance was defined as an index for the precision of the operation, and the operator’s fatigue level was obtained by subjective questionnaires. Each test subject’s precision index in Figure 6 was compared with the fatigue level in Table 3 (Figure 8). In Figure 8, the fatigue level is a combined fatigue level, obtained by adding the HMD or display fatigue and the glove fatigue.

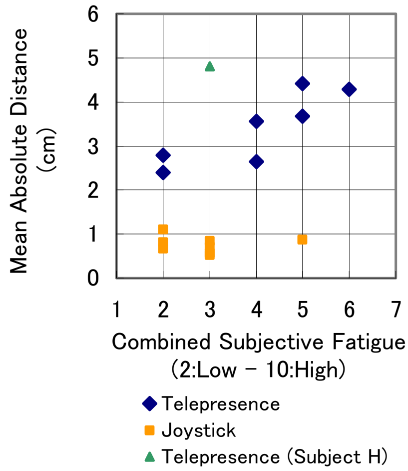


Figure 8 Comparison of precision and fatigue

The data for the telepresence interface shows a good correlation (0.86) between the precision and the fatigue, excluding test subject H. On the other hand, the data for the joystick interface shows almost no correlation (0.07). These results show that the fatigue level affected the precision of the operation more strongly with the telepresence interface.

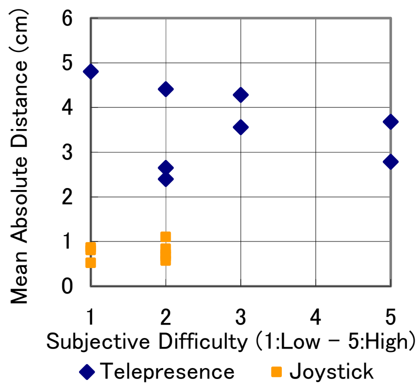


Figure 9 Comparison of precision and difficulty

The subjective sense of difficulty was also compared with the precision in Figure 9. A correlation for the telepresence interface was weakly observed (-0.28), while that for the joystick interface was not noticed (0.13). In contrast to our experience, a minus correlation appeared between the precision and the difficulty. This may be because there was a one-minute break between the trials, which worked as a recovery time for the test subjects' concentration. They were able to achieve a higher precision without losing needed concentration. If there were no break, the correlation might have turned out the other way around.

## 6. Conclusions

This experimental study yielded results regarding operator endurance with two different interfaces, a telepresence interface and a joystick interface. The joystick interface replaced the wrist sensor and the HMD of the telepresence interface with a force-reflection joystick and a flat display respectively. Focusing on the positioning of the hand, fingers were moved through a glove with both interfaces. A crank rotation task was selected as a test task, and eight test subjects performed a thirty-minute operation with each interface. Objective data and subjective questionnaires were obtained and compared to investigate if fatigue level or a sense of difficulty affected the precision for this specific task.

Objective results showed that, in general, better performance was observed with the joystick interface. Free motion was performed faster with the telepresence interface, and constrained motion was performed faster with the joystick interface. Subjective results show that glove fatigue was usually greater than the HMD or display fatigue and that the test subjects preferred the joystick interface, regardless of the operation time. In the questionnaires, the joystick interface was rated higher for precision, intuitiveness, and comfort, while the telepresence interface was rated higher for flexibility.

Comparison between the objective and subjective data revealed that as the test subject felt more fatigue, the precision of the operation decreased with the use of the telepresence interface. The subjective sense of difficulty also showed some correlation with the precision.

The above results were obtained for a specific task, hardware settings, and workstation configuration, and more experiments are needed for other tasks. However, the results still indicate that the operator endurance can be an important factor for a precise operation, especially in a long operation. The results also indicate that there is a good possibility of using other types of interfaces for anthropomorphic robot manipulation along with the telepresence interface. If an anthropomorphic robot were to perform a wide variety of tasks like a human, the operator would also need various support systems, depending on the task.

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