DSC-Vol. 55-1, Dynamic Systems and Control:
Volume 1
ASME 1994

EXPERIMENTS ON HUMAN PERFORMANCE IN TORQUE DISCRIMINATION AND CONTROL

Louise Jandura and Mandayam A. Srinivasan
Department of Mechanical Engineering
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT

Experiments to characterize human performance in sensing and controlling torque were performed using a computer-controlled device called the Instrumented ScrewDriver. The subjects held the handle of the device in a pinch grasp and overcame a preprogrammed resistive torque to rotate the handle. The Just Noticeable Difference for torque, a measure of human sensory resolution, was found to be about 12.7% when the reference torque was 60 mN-m. In experiments where the subjects had to control the torque they applied so as to maintain a constant angular velocity of the handle, the mean standard deviation of angular velocity was about 12.5% of the mean angular velocity, which was approximately the same as in the trials when the subjects were focusing on torque discrimination. The results are a part of ongoing studies on quantitative measurement of human performance relevant to the development of haptic interfaces for virtual environments or teleoperation.

1. INTRODUCTION

The human haptic system enables manual interactions with real or virtual environments. It consists of mechanical, sensory, motor, and cognitive subsystems. In general, haptic interactions involving the hand require activation of all of these subsystems.

Haptic interactions can be divided into two major categories: exploration and manipulation. Exploration has as its primary goal the perception of object properties. Although it requires well-controlled motor actions, it is a sensory-dominant task. Manipulation has as its primary goal the modification of the environment. Although sensory information is needed for good performance in manipulation, it is a motor-dominant task. Characterization of human performance during haptic interactions necessarily means the characterization of the sensory and motor systems individually and in combination.

When designing haptic interfaces for teleoperation or virtual environment systems, one needs to consider both sensory-dominant and motor-dominant behavior. Depending on the specifics of the task, overall task performance can be limited by either the sensory or motor system performance. Good design practice suggests that the specific characteristics of the haptic interface should match the capabilities of the human operator and assessment of human performance in both these areas provides quantitative guidelines for the engineering design of haptic interfaces. Moreover, a deeper understanding of the human sensory and motor systems provides clues concerning alternative schemes for conveying information back and forth across the human-machine interfaces.

The Just Noticeable Difference (JND) is a common measure of human sensory resolution and has been measured for a variety of physical parameters such as length, force, and compliance. See Tan, Pang, and Durlach (1992) for a review. To characterize human motor performance, different measures of the error between the desired signal and that generated by the human have been used. Work by Jones and Hunter (1992) has examined the relationship between the human perception of physical parameters such as stiffness, viscosity, and inertia and their effects on the operator's tracking performance. Srinivasan and Chen (1993) have measured the human ability to control the normal forces of contact exerted by the fingerpad under a variety of experimental conditions. In a series of experiments, Johansson and his colleagues (e.g., Johansson and Westling (1984), Johansson and Cole (1992)) have analyzed human control performance in experiments involving the grasping and lifting of objects using a two-finger pinch grasp. All of these experimental studies on human control provide both haptic and visual cues to the subjects. The work of Jones and Hunter and that of Srinivasan and Chen both required the tracking of force profiles displayed visually. Visual cues were also present in the studies by Johansson and Westling, although they were not an essential aspect of the task performed as in the tracking studies.

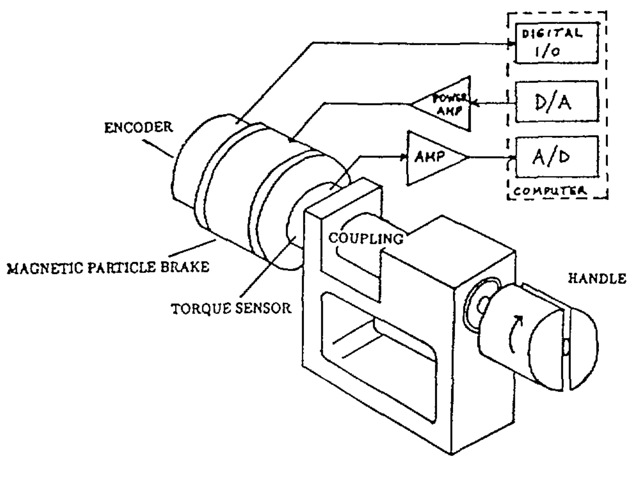

FIGURE 1: Sketch of the Instrumented ScrewDriver with a block diagram of its electronics.

This paper presents a series of experiments designed to measure the human ability to discriminate and control torque during precision haptic interactions. One major way in which this experimental paradigm differs from previous work in the area of human control performance is that it is purely in the haptic domain.

Specifically, this paper describes a new experimental apparatus, the Instrumented ScrewDriver, designed for the study of human performance in force/torque sensing and control tasks. A set of sensing and control experiments is presented and analyzed. A value of the human JND for torque is presented along with measures of human control performance.

2. EXPERIMENTAL APPARATUS

A sketch of the Instrumented ScrewDriver (ISD) and a block diagram of its electronics is shown in Figure 1. The ISD is comprised of a single horizontal shaft, which is supported by low friction bearings, and is connected to a reaction torque sensor (Transducer Techniques TRT 50) and a magnetic particle brake (Placid Industries B15-6-H). The particle brake is capable of generating a current-dependent braking torque of up to 3.4 Newton-meters (N-m) to be applied to the shaft with a maximum response time of 14 ms, and the torque sensor can measure up to 5.7 N-m of torque with a resolution of 1.4 milliNewton-meters (mN-m). The braking torque generated by the magnetic particle brake is referred to as the resistive torque. Because the signal measured by the torque sensor is the reaction torque, it is equal to the torque applied by the subject only when the shaft is stationary. Angular position of the shaft is measured with an incremental optical encoder (Dynamics Research T23-BA-6E-CB17-2500) with a resolution of 0.036 degrees (10,000 counts per revolution).

The user-end of the ISD shaft carries two half-cylindrical delrin fingerpads which form a cylindrical user interface with an outer diameter of 42 mm. The length of each half-cylinder is 50 mm, providing sufficient area for subjects to grasp the handle with their fingertips. The surface of the handle is very smooth, requiring subjects to pay careful attention to prevent slipping of their fingers on the handle.

The ISD is interfaced to a 80486 personal computer for stimulus delivery, control, and data acquisition in experiments. The torque sensor signal passes through an amplifier and is sampled by a 12-bit A/D converter at 1 kHz. The digital signal from the encoder is also sampled at 1 kHz using the circuitry on a motion controller board (Omnitech Robotics MC1000). The control signal to the magnetic particle brake is generated with a 12-bit D/A converter and a power amplifier which acts as a voltage-controlled current source.

3. EXPERIMENTAL PROCEDURE

In all the discrimination and control experiments, the subjects sat in front of the ISD and grasped the handle with their dominant hand (also the right hand for these subjects) in a pinch grasp with the thumb and index fingerpads. The subject's forearm was supported at a comfortable level about equal to the height of the ISD handle. Visual cues to the subject were eliminated by placing a screen between the subject and the ISD. There were no auditory cues.

3.1 Torque Discrimination

All torque discrimination experiments used a one-interval, two-alternative, forced-choice paradigm with no feedback to the subject. Based on some preliminary experiments, the reference torque τ_0 was chosen as 60 mN-m to ensure that its value was roughly half of the fatigue limit of human subjects for applying torque to the ISD handle in a pinch grasp. The positive torque increments $\Delta\tau$ presented in the discrimination experiments were 5%, 10%, 20%, and 30% of τ_0. In addition, training runs were conducted with $\Delta\tau$ equal to 50% of τ_0.

In each trial within a run of 64 trials, the subject was presented with either the reference stimulus τ_0 or the reference stimulus plus an increment $\tau_0 + \Delta\tau$. The value of $\Delta\tau$ was the same within a run. The subject turned the handle clockwise through 180 degrees against the constant resistive torque. At the end of 180 degrees of travel, the resistive torque was sharply increased to simulate a rigid stop. This was the signal to the subject that the trial had ended and that a response was needed. The subject typed 1 or 2 to indicate his or her judgement that the torque was the smaller or larger of the two torque levels, respectively. The order of the two stimuli presented was randomized, and each stimulus was presented an equal number of times within a run.

Three subjects, ages 20-30, were tested for 6 sessions each. Each session, consisting of 5 runs, lasted approximately 20-30 minutes and started with a training run with $\Delta\tau$ equal to 50% of τ_0. The subjects were informed of their overall performance at the end of each training run, but received no trial-by-trial feedback on their performance during the course of the training run. The criterion for successful completion of the training run was a 90% correct response by the subject. Only one of the subjects in one session (out of a total of 18 sessions) needed to repeat the training run.

After successfully completing the training run, the subject proceeded with 4 experimental runs of 64 trials each, one at each value of the $\Delta\tau$ increments. Subjects rested for a few minutes between runs in a session. The order of the presentation of the runs with different $\Delta\tau$ values was randomized within each session. A total number of 384 trials were conducted for each subject at each $\Delta\tau$ value.

During each trial in session 6, in addition to recording the stimulus and the subject's response, the resistive torque, the output of the torque sensor and the angular position of the shaft over time were also recorded.

3.2 Torque Control

The same experimental setup was used for experiments to measure the ability of subjects to control torque, but the instructions to the subjects were different. Each subject was asked to maintain a constant angular velocity while turning the shaft clockwise through 180 degrees against a constant value of resistive torque. The value of the angular velocity was up to the subject to choose, but they were asked to try and use the same value for each trial. Because of the physics of the ISD, attempting to maintain a constant angular velocity is directly related to attempting to apply and maintain a constant torque during shaft motion.

The experiment was done in one session for each of the same three subjects used previously. Stimuli consisting of constant resistive torque values were presented to each subject in 6 runs of 10 trials each. The resistive torques were at the same levels as those that were used in the discrimination experiments, and were presented in increasing order from the lowest to the highest torque (τ_0 followed by $\tau_0 + \Delta\tau$ with $\Delta\tau$ equal to 5%, then 10%, 20%, 30%, and 50%). As before, the resistive torque, the output of the torque sensor, and the angular position of the shaft were recorded over time.

4. RESULTS

The results of the torque discrimination experiments are listed in Table 1. The values of index of discrimination d' and response bias β are shown for each subject and also for the combined data from all the subjects at each value of $\Delta\tau/\tau_0$. Just Noticeable Difference (JND) is defined as the value of $\Delta\tau/\tau_0$ when d' is equal to 1. These performance measures come from the application of signal detection theory to psychophysical experiments. A response bias $\beta = 0$ indicates that the subject had no particular preference for judging the torques presented as the smaller or larger one, irrespective of its actual value. Given $\beta = 0$, $d' = 1$ corresponds to performance of approximately 75% correct responses in judging the relative torque levels. (Refer to Gescheider (1985) for a detailed discussion of applying signal detection theory to psychophysical experiments. See Tan et. al. (1992) for a summary of the data processing methods.)

Subject	DSL		JGD		JG		ALL
$\Delta\tau/\tau_0$	d'	β	d'	β	d'	β	d'
5%	0.64	-0.14	0.42	-0.18	0.55	-0.18	0.46
10%	0.98	-0.06	0.66	-0.04	1.06	-0.40	0.88
20%	1.75	-0.33	1.48	-0.16	1.67	-0.32	1.62
30%	2.27	-0.25	2.02	0.00	2.45	-0.45	2.19
50%	2.78	-0.09	3.27	0.17	3.43	-0.22	3.06
JND	11.2%		14.0%		11.1%		**12.7%**

TABLE 1: Summary of torque discrimination experimental results

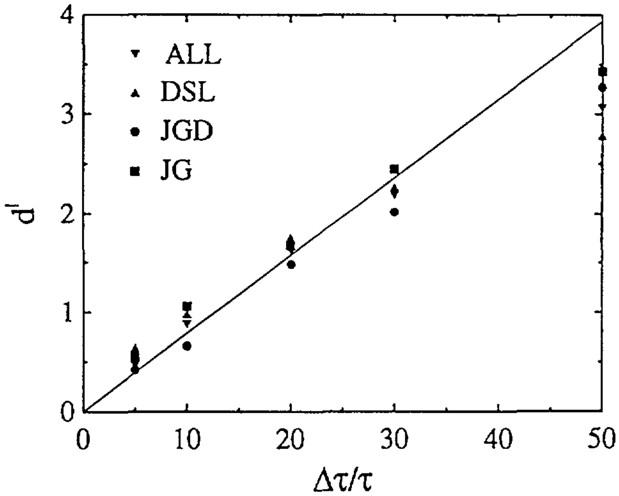

FIGURE 2: d' versus $\Delta\tau/\tau_0$ from the torque discrimination experiments

JND was calculated to be 11.1%, 11.2%, and 14.0% for the three subjects respectively and 12.7% for the data as a whole. The bias values tended to be small and negative for the most part. This means that the subjects tended slightly more often to perceive that the torque presented was the larger of the two, although both values had been presented an equal number of times.

Figure 2 shows d' plotted versus $\Delta\tau/\tau_0$ for each subject and for all the data. The straight line corresponds to the mean

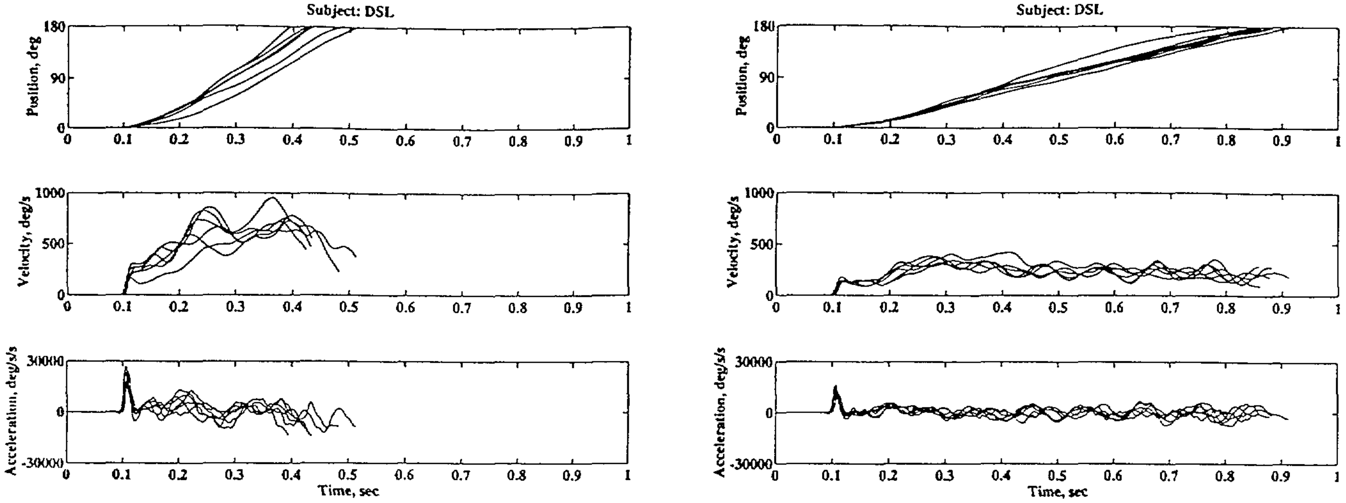

FIGURE 3: Angular position, velocity, and acceleration traces over time for subject DSL at a resistive torque level of 60 mN-m. Discrimination experiment trials are shown in the left graphs and control experiment trials are shown in the right graphs.

JND of 12.7%. The data points are clustered very close to this straight line and indicate low variability in discrimination performance among subjects. The JNDs for other values of the reference torque τ_0 need to be determined to verify if Weber's Law is satisfied.

Figures 3 - 6 compare the motor performance of two of the three subjects during some of the discrimination and control experiments. These two subjects were chosen because they demonstrate the extremes of performance observed in these experiments. Their motor performance is characterized by angular position, angular velocity, and angular acceleration profiles of the ISD shaft over time during experimental trials.

All the motor data shown in these figures are derived from the position data from the optical encoder. The encoder data was smoothed using spline functions and the method of generalized cross-validation to generate the smoothing parameter. (See Dohrmann, Busby, and Trujillo (1988) for a detailed description of this method.) Velocity and acceleration were found by simple, first-order differencing. The position data plotted in the figures is the smoothed data which is virtually indistinguishable from the original encoder data. The advantage of this method is that it produces clean and reliable velocity and acceleration signals.

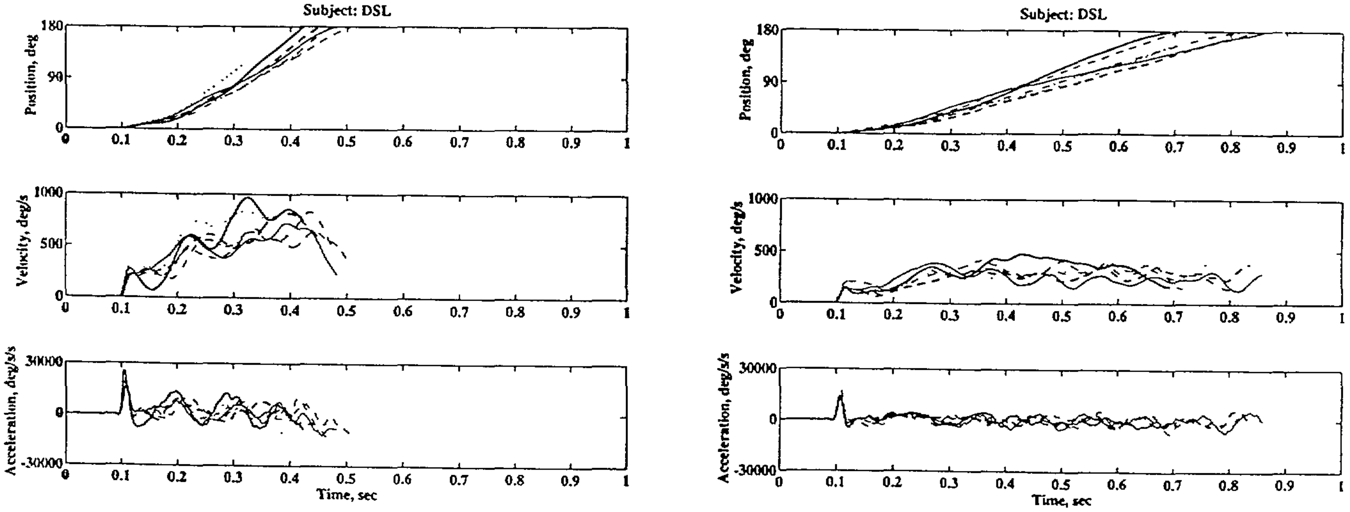

FIGURE 4: Angular position, velocity, and acceleration traces over time for subject DSL in discrimination experiment trials in the left graphs and in control experiment trials in the right graphs. Resistive torque levels are 60 mN-m (thin line), 63 mN-m (thick dashed line), 66 mN-m (thick line), 72 mN-m (dashdot), 78 mN-m (dotted), and 90 mN-m (thin dashed line).

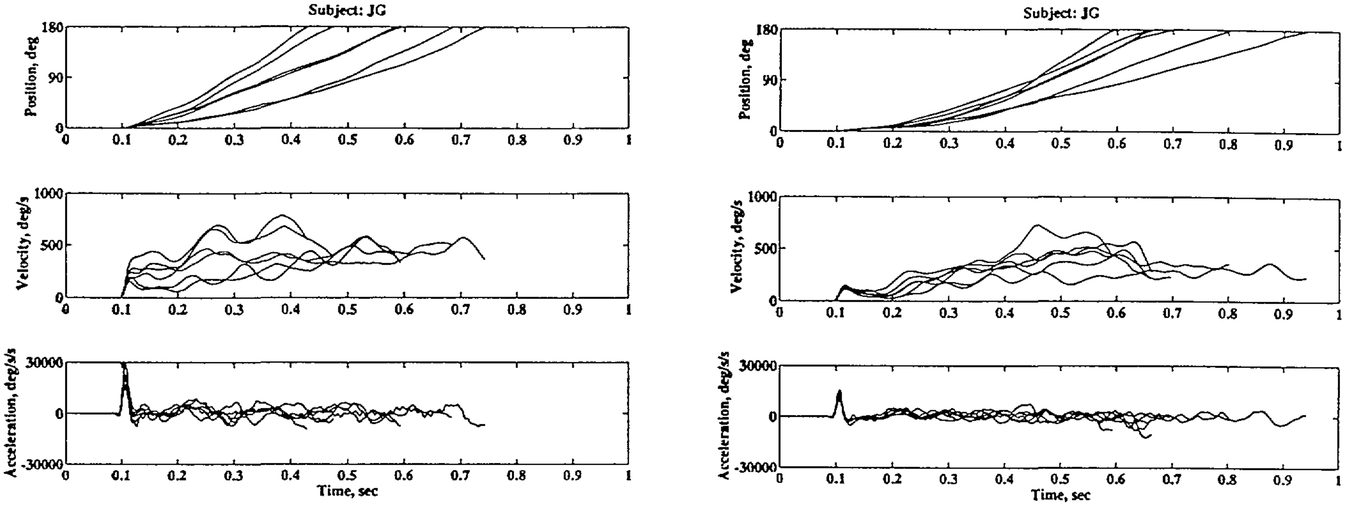

FIGURE 5: Angular position, velocity, and acceleration traces over time for subject JG at a resistive torque level of 60 mN-m. Discrimination experiment trials are shown in the left graphs and control experiment trials are shown in the right graphs.

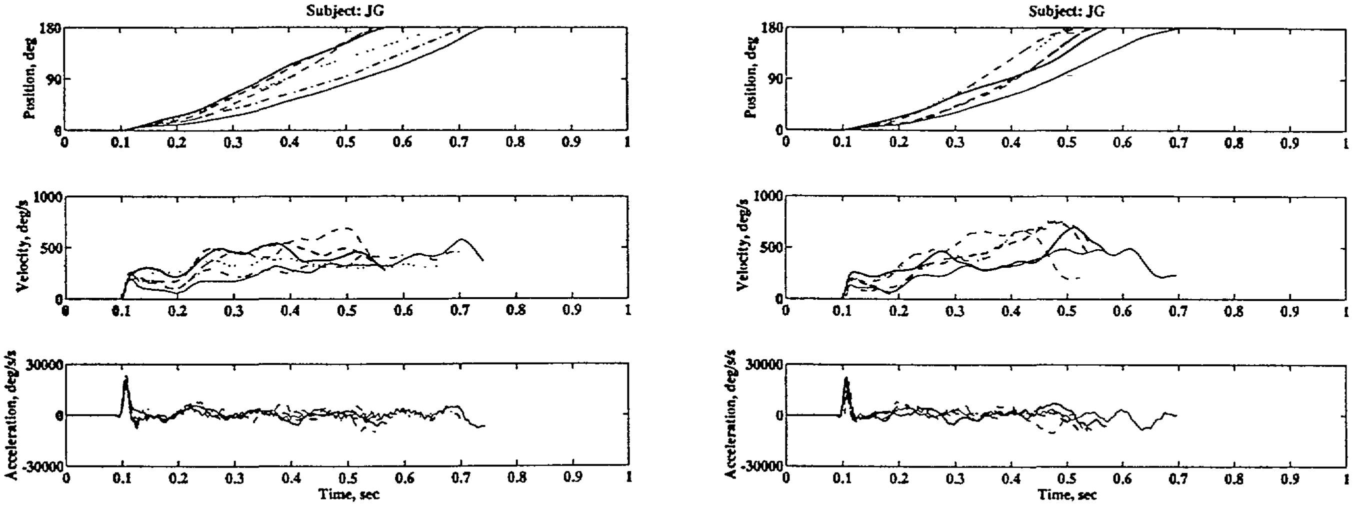

FIGURE 6: Angular position, velocity, and acceleration traces over time for subject JG in discrimination experiment trials in the left graphs and in control experiment trials in the right graphs. Resistive torque levels are 60 mN-m (thin line), 63 mN-m (thick dashed line), 66 mN-m (thick line), 72 mN-m (dashdot), 78 mN-m (dotted), and 90 mN-m (thin dashed line).

Resistive Torque = 60 mN-m						
Subject	DSL		JGD		JG	
Experiment	Discrimination	Control	Discrimination	Control	Discrimination	Control
Trial Time (ms)	347.5 ± 43	766.7 ± 36.2	738.7 ± 75.1	774.8 ± 126.2	485.5 ± 119.1	627 ± 125.5
Velocity (deg/s)	619.2 ± 71.1	257.9 ± 43.7	276.5 ± 58.1	293.3 ± 60.4	448.8 ± 116	411.7 ± 116.9
Std Dev (deg/s)	67.8 (10.9%)	44.8 (17.4%)	35.2 (12.7%)	33.9 (11.6%)	46.1 (10.3%)	49.3 (12.0%)

Resistive Torque = 90 mN-m						
Subject	DSL		JGD		JG	
Experiment	Discrimination	Control	Discrimination	Control	Discrimination	Control
Trial Time (ms)	443.7 ± 49.8	675.3 ± 44.7	823 ± 99.5	489 ± 38.9	447.5 ± 58.8	450.3 ± 49.6
Velocity (deg/s)	524.9 ± 64.8	297 ± 38.5	252.6 ± 45.8	483.2 ± 99.7	525 ± 89.9	586.4 ± 97.6
Std Dev (deg/s)	47.1 (9.0%)	52.3 (17.6%)	26.5 (10.5%)	61.8 (12.8%)	72.4 (13.8%)	83.4 (14.2%)

Ensemble of Resistive Torques (60, 63, 66, 72, 78, 90 mN-m)						
Subject	DSL		JGD		JG	
Experiment	Discrimination	Control	Discrimination	Control	Discrimination	Control
Trial Time (ms)	357.8 ± 38.4	681.3 ± 67.7	705 ± 45	600.5 ± 88.6	533 ± 84.1	463.3 ± 69.7
Velocity (deg/s)	634 ± 128.8	313.2 ± 71	308.3 ± 29.1	356.3 ± 43.9	416.8 ± 83.6	493.9 ± 103.2
Std Dev (deg/s)	78.3 (12.4%)	38.9 (12.4%)	33.6 (10.9%)	40.8 (11.5%)	42.4 (10.2%)	66.7 (13.5%)

TABLE 2: Summary of motor performance measures. Mean trial time and angular velocity over 6 trials are displayed along with ± 1 standard deviation. The mean standard deviation of the angular velocity over 6 trials and its percentage of the mean angular velocity are also shown.

Figures 3 and 5 show the motor performance of subjects DSL and JG respectively during both the discrimination and control experiments for trials when the resistive torque was 60 mN-m (the reference torque). Six typical trials for each condition is shown. These trials were chosen by the authors from the complete data set as representative of the entire set. Qualitatively, the general shape of the traces for each variable is similar across experimental conditions and subjects. The very early part of the position, velocity, and acceleration curves are very consistent, with the initial slopes being about the same in all cases. The position curves start with an initial acceleration and then flatten out to a relatively constant velocity. This behavior is apparent in the velocity and acceleration traces. The acceleration has a large initial peak of about 25 milliseconds in duration.

Subject DSL performed the discrimination trials nearly twice as fast as the control trials with the duration being about 0.3 to 0.4 seconds for the discrimination trials as compared to about 0.7 to 0.8 seconds for the control trials. There is a reasonable amount of repeatability in both sets of data. The data for Subject JG shows much more variability than that of DSL. Subject JG also tended to perform discrimination trials more quickly than control trials but the difference is much less distinct than with subject DSL. The trial-to-trial variability in performance appears to be about the same for this subject for both discrimination and control trials. In fact it is difficult to tell them apart.

Figures 4 and 6 show the motor behavior of subjects DSL and JG during both the discrimination and control experiments for an ensemble of trials consisting of one trial at each of the six levels of resistive torque used in the experiments (60, 63, 66, 72, 78, and 90 mN-m). Again these trials were chosen as typical ones to represent the entire data set. This motor data is very similar to that shown in Figures 3 and 5. There is no apparent difference in motor performance at different resistive torque levels for either subject.

One curious phenomenon observed rather consistently in all of the data is the occurrence of peaks in the velocity and acceleration profiles at about 0.1 second intervals. Further investigation is needed into the source of these peaks, which may provide some insights into mechanisms of motor behavior.

In order to better evaluate the differences in performance, some quantitative measures have been defined and evaluated for the data sets shown in Figures 3 - 6. In addition, motor data for both discrimination and control trials for six typical trials when the resistive torque was 90 mN-m was analyzed for subjects DSL and JG. The performance of a third subject, JGD, has also been included in the quantitative analysis. The results are displayed in Table 2.

In this analysis, performance during each experimental trial was characterized by three numbers. One is the time taken to complete a trial (0 degrees to 180 degrees). The two others are the mean and standard deviation of the angular velocity between the 60 degree position and the 120 degree position of the handle. This portion of the trial has been chosen to avoid any startup or ending transients and generally looks to be the most consistent portion of each velocity trace.

Given these statistics for each trial we define the following measures, which in all cases are the average of six trials and are intended to summarize each set of data for a particular subject and a given set of experimental conditions. First is the mean time to complete a 180 degree rotation, which is referred to as the mean trial time, and its standard deviation, which are taken over the six individual trials in each set. It is a measure of trial-to-trial consistency in motor performance. The second measure is the mean angular velocity and its standard deviation among the six individual trials. This measure is an indication of how consistently the same velocity is chosen across trials. The final measure is the mean of the standard deviations of angular velocity in each of the six individual trials. It is an average measure of variation in angular velocity within a trial and is an indication of the motor performance during discrimination and control trials. This measure is also expressed as a percentage of the mean angular velocity in Table 2.

The mean trial times varied between about 350 to 830 msec in the nine data sets. In five data sets, the mean trial times for control experiments were longer than those for discrimination experiments, whereas in three data sets the result was reversed and in one the mean trial times were about the same.

The mean angular velocities varied between about 250 to 630 degrees/s across all the subjects. The variation between data sets by the same subject was somewhat narrower.

The mean of the standard deviations of angular velocity, expressed as a percentage of the mean velocity, ranged from 9 to 17.6% but was typically 10 to 14%. There is no particular pattern in its variation across either subjects or resistive torque levels. Surprisingly, the percentage was generally a little higher for the control data sets, but the statistical significance of this needs to be tested.

5. CONCLUSIONS

The JND for torque was found to be 12.7% when the reference torque was 60 mN-m. This is higher than the force JND of 6-8% generally reported in the literature (Pang et. al. (1991), Tan et. al. (1992)).

Comparison of the time profiles of angular velocity from the torque discrimination experiments (a sensory-dominant task) and those from the torque control experiments (a motor-dominant task) reveal that even when the subjects were trying to maintain a constant angular velocity in the latter set of experiments, their performance was no better than when they were trying to discriminate the torques. An implication is that during torque discrimination, the subjects tend to maintain a constant angular velocity to the best of their motor ability.

REFERENCES

Dohrmann, C. R., Busby, H. R., and Trujillo, D. M., "Smoothing noisy data using dynamic programming and generalized cross-validation," *Journal of Biomechanical Engineering*, vol. 110, pp. 37–41, **1988**.

Gescheider, G. A., *Psychophysics: Method, Theory, and Application (2nd ed.)*, Lawrence Erlbaum Associates, Hillsdale, NJ, **1985**.

Johansson, R. S. and Cole, K. J., "Sensory-motor coordination during grasping and manipulative actions," *Current Opinion in Neurobiology*, vol. 2, pp. 815–823, **1992**.

Johansson, R. S. and Westling, G., "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Exp. Brain Res.*, vol. 56, pp. 550–565, **1984**.

Jones, L. A. and Hunter, I. W., "Human operator perception of mechanical variables and their effects on tracking performance," *Advances in Robotics*, vol. 42, pp. 49–53, **1992**.

Pang, X. D., Tan, H. Z., and Durlach, N. I., "Manual discrimination of force using active finger motion," *Perception and Psychophysics*, vol. 49, no. 6, pp. 531–540, **1991**.

Srinivasan, M. A. and Chen, J., "Human performance in controlling normal forces of contact with rigid objects," *Advances in Robotics, Mechatronics, and Haptic Interfaces*, vol. 49, pp. 119–125, **1993**.

Tan, H. Z., Pang, X. D., and Durlach, N. I., "Manual resolution of length, force, and compliance," *Advances in Robotics*, vol. 42, pp. 13–18, **1992**.

ACKNOWLEDGEMENTS

The work reported here was supported by the ONR grant N00014-92-J-1814. The authors wish to thank Akhil Madhani for designing and building the mechanical portion of the ISD, Hong Tan and Lee Beauregard for their help with the torque discrimination experiments, and Kiran Dandekar for his assistance in preparing this document.