Short Papers

The Influence of Teleoperator Stiffness and Damping on Object Discrimination

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***Abstract*—Human task performance using teleoperator systems depends on the physical and controlled parameters of the system. Two teleoperated grasping tasks—size and stiffness discrimination—were studied to investigate how changes in system parameters influence human capabilities. The device characteristics altered were teleoperator stiffness (size and stiffness discrimination) and teleoperator damping (size discrimination only). It was found that neither teleoperator stiffness nor teleoperator damping influenced size discrimination. Also, teleoperator stiffness did not influence stiffness discrimination. Furthermore, teleoperated performance was compared with direct interaction using bare hands or with the fingers in a bracket. Size discrimination performance was equivalent for these three conditions, but stiffness discrimination performance was lower for teleoperation than for direct interaction.**

***Index Terms*—Haptics, perception, teleoperation.**

I. Introduction

Haptic teleoperators transmit interaction forces between a human operator and a remote environment. It is obvious that haptic feedback, e.g., forces, vibrations, etc., to the operator would improve task performance, but it is still unclear how accurate the haptic feedback must be in order to support the operator to perform a remote task.

A teleoperator will always induce some distortion on how the remote environment is experienced by the operator, similar to how a mechanical tool would. The teleoperator stiffness is not infinite, and the damping is not zero for any real implementation. This electromechanical filtering has been characterized using a number of device performance measures [1]–[3], where it is assumed that higher "fidelity" in reproducing the environment impedance is better. However, for at least one virtual reality identification task, it has been shown that for the improvement of the haptic device, there is no correlated improvement of human task performance. The study by O'Malley and Goldfarb [4] investigated how the controlled stiffness of a haptic device influenced human size discrimination performance in a stylus task. They found that humans performed equally well down to a stiffness of 0.4 N/mm, below which the performance dropped.

One important subtask in telemanipulation is object identification by *grasping*. We assume that kinaesthetic object identification is mainly done by using a combination of stiffness and size discrimination. It is not known if the results of O'Malley and Goldfarb's stylus task, where the interaction is mainly shear forces could also extend to grasping, where forces are perpendicular to the finger pad surface. LaMotte [5] studied stiffness discrimination using bare hands compared with using a stylus-like tool, and found that the performance was better for the tool-based interaction. Also in that study, the tool induced shear forces on the finger pads, while the bare hands condition—pressing with the finger—mainly generated perpendicular forces.

In the study of Berryman *et al.* [6], size discrimination for direct manipulation was investigated in detail, and their results suggest that the stiffness of an object does not influence human size discrimination performance. They attribute the size discrimination performance to the perceived spread of the fingers at the moment of contact. This suggests that for teleoperated object identification, the total teleoperator stiffness should be of low importance, as long as the moment of contact can be perceived clearly. The teleoperator stiffness and damping both relate to the perceived finger spread as well as the detection of the contact.

The goal of this research is to quantify the influence of teleoperator stiffness and damping on object discrimination during grasping in a size and stiffness discrimination task.

II. Method and Materials

To quantify the relationship between teleoperator stiffness and damping and human performance, three human factor experiments were performed. Size discrimination was studied for varying teleoperator stiffness (experiment A) and varying damping (B). Stiffness discrimination was studied for varying teleoperator stiffness (C).

In each experiment, different naive subjects performed the grasping tasks after a brief familiarization with the experimental apparatus and after giving consent to participate. In experiment A, six subjects participated, and in experiments B and C, there were ten subjects. Each experiment was performed using the dominant hand. A screen blocked visual feedback to ensure that only haptic feedback was present.

For all experiments, the task was a discrimination task where two objects were felt and the subject would try to detect a difference in size or stiffness. First, a reference would be felt, and then, an unknown object, whereupon the subject would indicate if the second one was bigger or smaller (alternatively, stiffer or softer) than the reference in a two-way forced-choice test. The human performance for the tasks was quantified as *percentage correct responses*, which varies from 50% (random guessing) for indistinguishable differences to 100%, when the subjects answer correctly every time.

The main factor (difference in performance between the teleoperated conditions) of the experiment was tested using the analysis of variance (ANOVA), and a p-value of less than 0.05 was considered to be significant. For experiments A and B, one-way ANOVA was used, and for experiment C, two-way ANOVA was used.

In addition to the teleoperated settings, two reference conditions were included, *bare hands* and *brackets* (see Fig. 1). The *bare hands condition* means that the subject felt the test objects with their bare hands. This condition has been extensively studied, and allows comparison of the results of this study with previous research [7]. The *brackets condition* means that the master device of the teleoperator was used as a position sensor and the test object was placed between the bracketed fingers. In haptic devices, thimbles are often used to interface with the finger pad, but Howe has shown [8] that pretension of the mechanoreceptors reduces the perception of contact. Therefore, the brackets were designed to minimize the preload. A t-test was used to compare each of the reference conditions with the teleoperated conditions. Also, a p-value of less than 0.05 was considered to be significant here.

In Fig. 2, our experimental teleoperation system is shown.

The experiments were performed using a 1-DOF teleoperator (see Fig. 2). The teleoperator was originally designed for experiments

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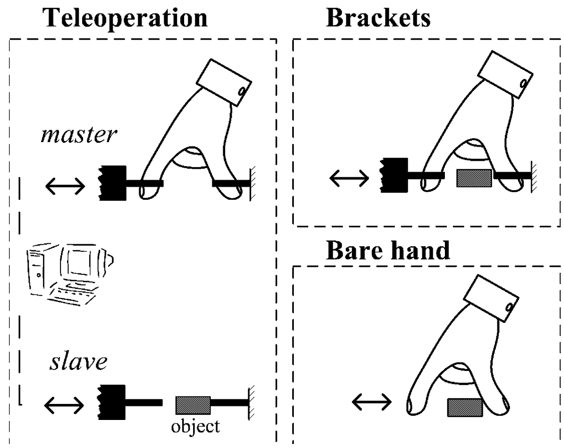

Fig. 1. (Left) Teleoperation conditions are the main factors of the experiment. Furthermore, performance with (top right) fingers in the brackets of the master and (bottom right) with the bare hand are used as reference.

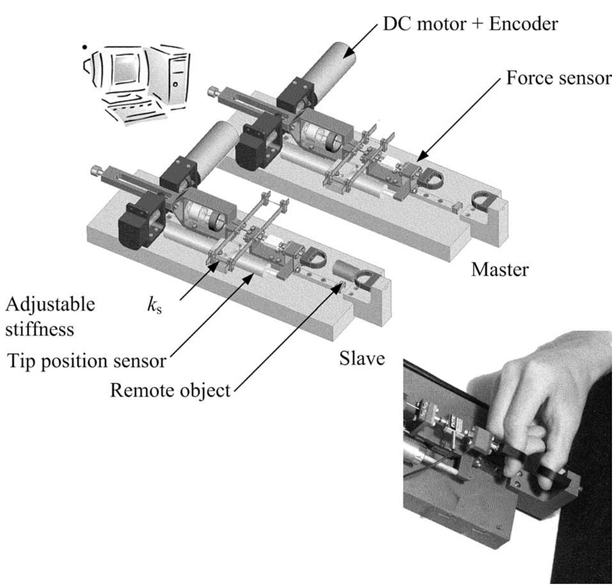

Fig. 2. Experimental setup used in the experiments. It is a single-DOF haptic teleoperation device with adjustable mechanical stiffness on the slave (k_s).

that required variable slave device stiffness, both through control gain and intrinsic stiffness. By varying the teleoperator control gains and the intrinsic stiffness, the total teleoperator stiffness and damping can be adjusted. Later, in experiment A, the stiffness contribution from the slave stiffness and the controlled stiffness are compared, and it is verified that a lumped model is sufficient for the purpose of this study. The mechanics of the teleoperator and control schemes are explained in detail in [9] and [10].

The main characteristics of the teleoperator dynamics can be approximated by a *teleoperator mass* ($\hat{m}$), *teleoperator stiffness*($\hat{k}$), and *teleoperator damping* ($\hat{b}$). For each experimental condition, realized by a certain controller setting and a certain slave stiffness, the total teleoperator stiffness and damping were measured at the master side six times to get a mean value and standard deviation (see Tables I and II). In all experiments, the teleoperator mass was 0.40 kg $\pm$ 5%.

The analysis of the teleoperator is done using the H-matrix model [11], which is a complete linear model of the teleoperator for each given controller. Each condition in the experiments has a different physical

TABLE I
EXPERIMENT A (AND C): TELEOPERATOR STIFFNESS

Setting	*Teleoperator Stiffness* $\hat{k}$ [N/mm] $\pm 6\%$	*Z-width* $\pm 5\%$
A1 (C1)	0.15	33.1
A2 (C2)	0.30	42.7
A3 (C3)	0.60	53.2
A4	1.10	63.8
A5 (C4)	1.20	64.6
A6	2.50	77.1
A7	7.50	95.8
A8	32.0	126
A9	brackets	n/a
A10	bare hands	n/a

TABLE II
EXPERIMENT B: TELEOPERATOR DAMPING

Setting	*Teleoperator Damping* $\hat{b}$ [Ns/m] $\pm 8\%$	*Z-width*
B1	15	56.3
B2	10	62.5
B3	5	71.5
B4	1	83.9
B5	brackets	n/a
B6	bare hands	n/a

or controlled stiffness and damping, so for each condition, a different H-matrix is calculated. To further illustrate the relationship between the human task performance and a more generalized device performance, the impedance width, *Z-width*, introduced by Colgate and Brown [12] is used. The Z-width is a measure of the range of impedances that can be displayed to the operator. The limits, the minimum impedance with the slave moving in free air ($Z_{\mathrm{to,free}}$) and the maximum impedance, in hard contact with a stiff wall ($Z_{\mathrm{to,stiff}}$) are illustrated in Fig. 3. The integrated difference between the magnitude of the two impedances is the *Z-width* of the teleoperator

$$Z_{\mathrm{width}} = \int_{\omega_0}^{\omega_1} \left|\log|Z_{\mathrm{to,stiff}}(j\,\omega)| - \log|Z_{\mathrm{to,free}}(j\,\omega)|\right| d\omega. \quad (1)$$

The larger the Z-width, the richer the information presented to the operator. The Z-width can be increased in many ways. In this paper, two common ways are presented: either by increasing the teleoperator stiffness or by decreasing damping (see Fig. 3). To illustrate the influence of the Z-width on task performance, a linear regression of the results of the experiments (A–C) was performed and is presented in Section III-D.

A. Experiment A—Size Discrimination Versus Teleoperator Stiffness

Eight different teleoperator stiffnesses were implemented according to Table I, ranging from 0.15 to 32 N/mm. Furthermore, to allow comparison between the contribution to the total teleoperator stiffness from intrinsic stiffness and controlled stiffness, two different slave stiffnesses (k_s) were used: for conditions A6 and A8, the slave stiffness was the highest possible ($k_s = 105$ N/mm $\pm 8\%$). For the other six conditions (A1–A5 and A7), the slave stiffness was set to a relatively low value ($k_s = 1.12$ N/mm $\pm 4\%$). For illustration, the variation of the Z-width is shown in Fig. 4. The damping was 5 N·s/m for all conditions in experiments A and C.

For each condition, the size discrimination task was performed 18 times, following a prerandomized sequence. The reference was always 30 mm and six other objects (27–29 mm, 31–33 mm) were used, three

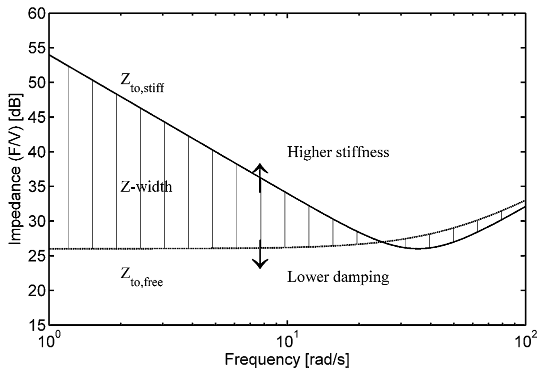

Fig. 3. Dynamic range of the teleoperator. The Z-width is improved by increasing the teleoperator stiffness ($\hat{k}$) or by decreasing the teleoperator damping ($\hat{b}$).

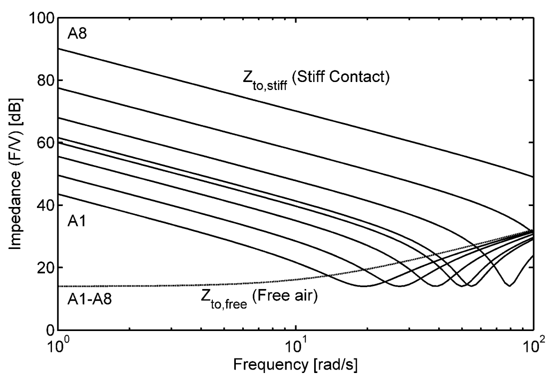

Fig. 4. Teleoperator stiffness and Z-width variation of experiment A: the Z-width increases three times.

times each. In total, for the ten conditions, each subject performed the size discrimination task 180 times.

B. Experiment B—Size Discrimination Versus Teleoperator Damping

Ten subjects participated in the size discrimination experiment with varying damping. The damping of the teleoperator was implemented as controlled damping, in the range from 1.0 to 15 N·s/m (see Table II). The variation in Z-width for experiment B is shown in Fig. 5. The stiffness in this experiment was set to the highest possible (32 N/mm).

C. Experiment C—Stiffness Discrimination Versus Teleoperator Stiffness

Ten subjects participated in the stiffness discrimination experiment. The teleoperator stiffness in the experimental conditions C1–C4 are identical with the settings A1, A2, A3 and A5 (see Table I). The objects to discriminate were custom-made wire springs with equal size (30 mm) and different stiffness. In this experiment, two different reference objects (k_e) were used, one in the softer (C_{low}) and one in the stiffer (C_{high}) range of the teleoperator stiffness (see Table III).

III. Results

A. Experiment A—Size Discrimination Versus Stiffness

The size discrimination performance for different teleoperator stiffness conditions was compared using ANOVA, and there was no difference between the conditions. Furthermore, the teleoperation performance (A1–A8) was compared with the brackets (A9) and with bare

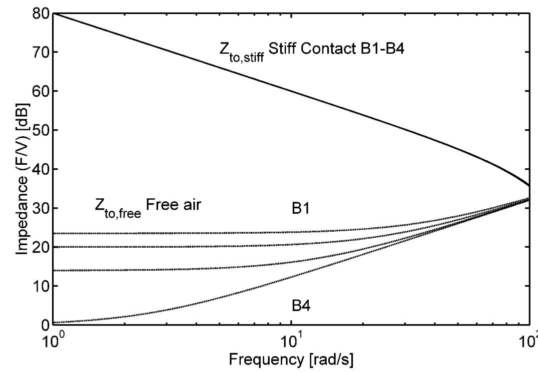

Fig. 5. Teleoperator damping and Z-width variation in experiment B.

TABLE III
EXPERIMENT C: OBJECT PAIRS FOR STIFFNESS DISCRIMINATION

Group	*Object pair*	*Reference* k_e[N/mm] $\pm 3\%$	*Test object* k_e[N/mm] $\pm 3\%$
C_{low}	1	0.35	0.21
	2	0.35	0.27
	3	0.35	0.40
	4	0.35	0.49
C_{high}	5	1.20	0.88
	6	1.20	1.08
	7	1.20	1.41
	8	1.20	1.81

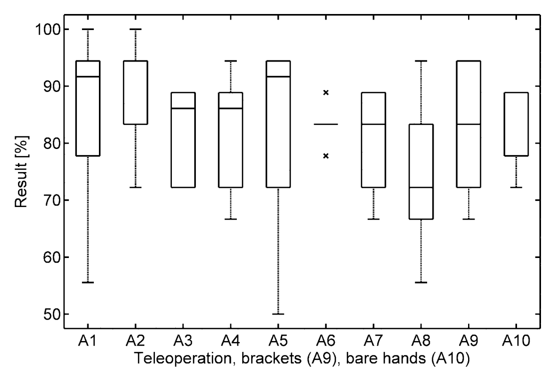

Fig. 6. Size discrimination performance for stiffness setting (A1–A8), and reference conditions brackets (A9) and bare hands (A10). There was no significant difference between the conditions.

hands (A10) using t-tests, and there was no difference here also. A boxplot of the subjects' performance for the conditions of experiment A is presented in Fig. 6.

B. Experiment B—Size Discrimination Versus Damping

The size discrimination performance for the six conditions is shown in Fig. 7. The ANOVA on the four teleoperated conditions revealed no significant difference. When comparing the teleoperation conditions with the references using t-test, the teleoperation performance was better than the bare hands condition ($t_{68,0.025} = 2.10$, $p = 0.039$) but was equal to the bracket condition.

C. Experiment C—Stiffness Discrimination Versus Stiffness

The performance of the subjects in the stiffness discrimination task is shown in Fig. 8. All teleoperation conditions, for both C_{low} and

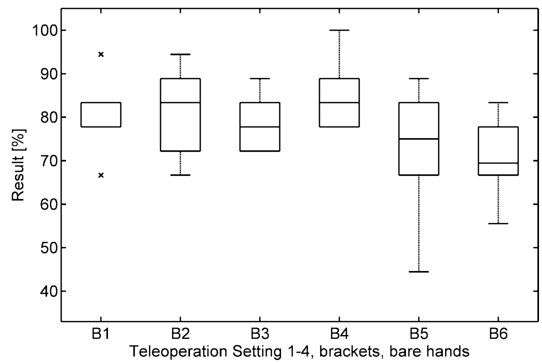

Fig. 7. Size discrimination performance for the damping conditions. There was a significant difference ($p = 0.039$) between the teleoperation settings and the bare hand condition.

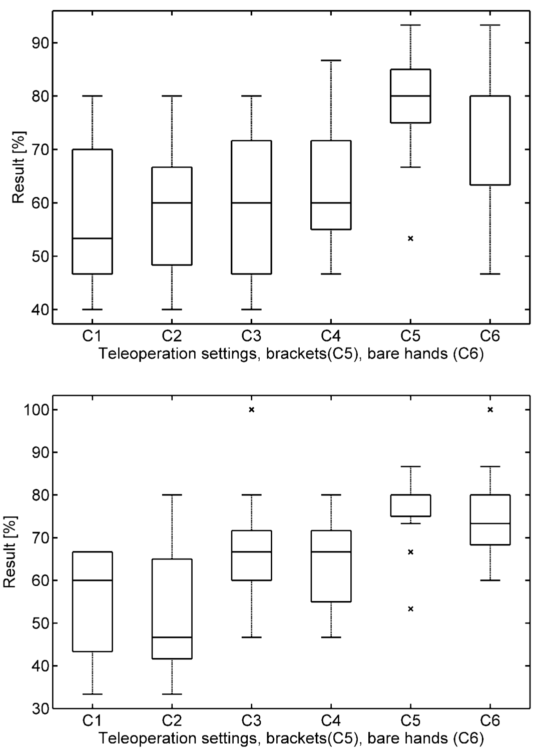

Fig. 8. (Top) Experiment $C_{\rm low}$ and (bottom) $C_{\rm high}$. Stiffness discrimination for the two different reference objects. There was no difference between the stiffness conditions (C1–C4) only compared with bare hands (C5) and brackets (C6).

$C_{\rm high}$, were compared using a two-way ANOVA, and there was no difference in performance.

In the comparison between the teleoperation conditions and the references, the t-test did show a significant difference when compared both with the bare hands ($t_{31,0.025} = -3.33, p = 0.002$) and the brackets ($t_{31,0.025} = -4.88$, $p < 0.001$) conditions.

D. Device Performance Versus Human Performance

Is there any relationship between the device performance measures and the human task performance? In the experiments reported, there was no significant difference between the conditions, taken as independent groups, but using regression, trends can become visible. For each of the conditions in the three experiments, the average human task

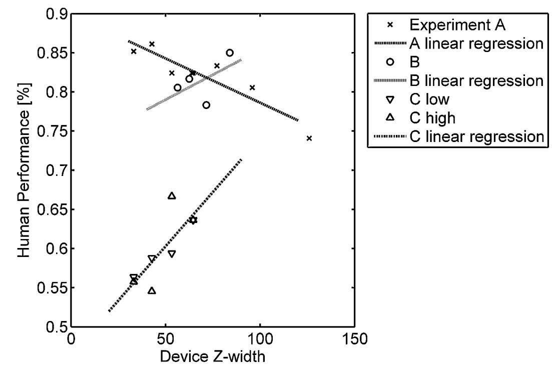

Fig. 9. Average task performance versus Z-width of the teleoperator for all the settings in experiments A–C. According to the current theory, the human task performance should increase with increased Z-width.

performance was calculated and a regression line was plotted against the Z-width (see Fig. 9). For experiment A—size discrimination with varying teleoperator stiffness—the performance actually seems to decrease slightly with improved "device performance." For experiment B—size discrimination with varying teleoperator damping—there are only four data points, which makes it difficult to determine any trend. Only for the stiffness discrimination of experiment C, there seems to be a clear positive influence from the increased Z-width.

IV. Discussion

Teleoperated size discrimination of stiff objects is apparently not very difficult. Even with a very low teleoperator stiffness, or even with considerable damping, the human task performance was equal or better than direct manipulation with bare hands. This confirms and extends the findings of O'Malley and Goldfarb [4] and Berryman *et al.* [6]. However, the expected stiffness threshold around 0.4 N/mm, below which the performance would deteriorate was not found in this study. This is probably because size discrimination is easier for two-finger grasping than when using a stylus.

There was also no measurable difference between the performance in the settings using mechanical stiffness compared with controlled stiffness to achieve a certain total teleoperator stiffness. It means that regarding size discrimination performance, the teleoperator designer has a choice where to put the stiffness in the system—either using physical compliant element or in the controller. Physical compliance has some advantage for stability [13]. Of course, size discrimination is only one subtask in teleoperation in general, and a low-stiffness system has other disadvantages, such as a low-frequency resonant mode and difficulty in applying large forces.

Another finding of this study was that some high-stiffness, low-damping conditions gave better performance than with bare hands. It suggests that a well-designed mechanical filter can help the human in certain tasks. This is in contrast to most of the teleoperation literature, where it is assumed that human operators perform worse in teleoperation than with direct manipulation using their bare hands. This can be explained in the framework of Berryman *et al.* [6], in the sense that a tool can improve the perception of the contact with the object. The high-frequency force information of the impact is a strong cue that helps distinguish the object boundary.

Stiffness discrimination, on the other hand, was more difficult than expected. Even though earlier studies with direct manipulation indicate that a difference of 15%–30%, as in this study, would be detected easily [14], the subjects had considerable difficulty in discriminating the stiffnesses, especially for the low-stiffness teleoperation conditions.

There is no clear positive correlation between the teleoperator performance measure Z-width and the human performance. Device performance measures are generally based on the assumption that a one-to-one transmission of force and velocity signals is the best support a human operator can have. Probably that is not the case for all tasks. It has been suggested [15] that enhancement of estimated stiffness information, a nonlinear mapping of contact forces, can improve teleoperated performance in certain tasks. In other human support systems, e.g., flight simulators, frequency-specific filters are used to amplify selected parts of the information stream, tuned to the perceptual capabilities of human pilots and the output capabilities of the motion platforms. Similar methods could be applied for haptic teleoperation.

V. Conclusion

The results show the following.

1) Variation in teleoperator stiffness and damping does not influence teleoperated task performance for any of the tasks.
2) Teleoperated performance with high or low stiffness is not significantly different from bare hand performance for the size discrimination task.
3) Teleoperation with low damping improves size discrimination performance compared to using the bare hands.
4) Bare hands or brackets are significantly better than teleoperation for discrimination of stiffness.

It means that the minimum design requirements for size discrimination tasks allows for a very low teleoperator stiffness, but higher stiffness is necessary for accurate stiffness discrimination.

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