INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION
2019, VOL. 35, NO. 12, 1061–1073
https://doi.org/10.1080/10447318.2018.1509499

Taylor & Francis
Taylor & Francis Group

Proposal of an Index for the Operator's Haptic Sensation in a Master-Slave System with Force-Feedback Function

Dongbo Zhou [a] and Kotaro Tadano [b]

[a]Department of Mechano-Micro Engineering, Tokyo Institute of Technology, Yokohama, Japan; [b]Institute of Innovative Research, Tokyo Institute of Technology, Yokohama, Japan

ABSTRACT
This article proposes an index to estimate the operator's haptic sensation of the contact between the slave device and the environment in operating master–slave systems with force feedback function. The index value is derived from the velocity information of the master device before and after contact, which is hypothesized to represent the intensity of haptic sensation stimuli presented to the operator. Two characteristics of this index are discussed by means of psychophysics experiment, which are the statistical characteristics of the index value for different operators, and how the change in the operator's haptic sensation is reflected on the index value. The index is validated by another psychophysics experiment. The experimental results show that the performance of operator's haptic sensation can be predicted correctly based on the proposed index value. This index is expected to be applied in the parameter design of bilateral-control systems with force feedback function.

KEYWORDS
Master–slave system; force feedback; haptic sensation; parameters design

1. Introduction

The benefit of force feedback function in master–slave robot systems has been studied extensively. For example, in robot-assisted surgery, force feedback can reduce unwanted tissue damage (Wagner, Stylopoulos, Jackson, & Howe, 2007). In tasks beyond a human's capability or access, such as micro-manipulation (Bolopoin & Regnier, 2013) and deep-sea environments (Kuiper, Frumau, Van Der Helm, & Abbink, 2013), force-feedback function can enhance efficiency and overall task performance.

Impedance-adjusting bilateral control is a common method for providing a force-feedback function (Beretta, Nessi, Ferrigno, & De Momi, 2015). Systematic impedance is adjusted according to the requirements of different tasks or personal preferences when using such systems. For example, increasing the damping parameter of the master device can decrease hand vibration, or decreasing the impedance between the master and the slave can reduce the impact of the slave device on the environment.

Optimization of the combination of parameters involved in impedance control has been studied in the past (Zotovic Stanisic & Valera Fernandez, 2012; Zotovic Stanisic, Valera Fernandez, & Garc´Ia Gil, 2005). However, these studies focused only on the performance and protection of the robot and did not consider the perspective of the human factor, since the operation is executed by the operator, human factors should also be considered.

During operating the master-slave systems with force feedback function, when the slave devices contact with the environment. The haptic sensation, in this paper we defined as how easily with which an operator can sense the contact between slave device and the environment, is an important human factor, because a clear sensation of contact plays an important in determining spatial position and orientation of object. (Wildenbeest, Abbink, Heemskerk, Van Der Helm, & Boessenkool, 2013).

Obviously, the operator's haptic sensation will be affected after the systematic parameters adjustment. For example, a low system impedance between the master and slave devices is necessary to reduce the impact force between a slave device and its environment, but setting the system impedance too low may obscure the haptic sensation for the contact. In another case, high force amplification can enhance the haptic sensation of the operator at the risk of generating a dangerous shock in case of a surprisingly strong interaction with the environment.

The operator's haptic sensation should, therefore, be considered when adjusting system parameters. As a guideline for parameters adjustment, some qualitative effects of increasing systematic parameters on haptic sensation are listed in Table 1.

However, based on the qualitative effects, systematic parameters can only optimized with trial-and-error adjustments. A quantitative guideline that relates haptic sensation to systematic parameters is needed to quantify and objectify the parameter-adjustment processes instead of trial-and-error. To realize this, we intend to use an index to quantify the operator's haptic sensation, and to clarify the relationship between systematic parameters and the index.

CONTACT Dongbo Zhou zhou.d.aa@m.titech.ac.jp Department of Mechano-Micro Engineering, Tokyo Institute of Technology, 226-8503, R2-46, Nagatsutacho 4259, Yokohama, Japan.
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/hihc.

Table 1. Qualitative effects of parameters upon haptic sensation.

System Parameter Increased	Effect on Operator's Haptic Sensation
Master damping	Weaken
Master-slave impedance	Strengthen
Position amplification	Strengthen
Force amplification	Strengthen

1.1. Related works

Many indices and indicating method with regard to operator's haptic performance are proposed.

Transparency is a widely-used index that guides the system parameter design with regard to human factors. Many studies have proposed transparency as a performance index for evaluating control architectures and a framework for parameter design. (Hashtrudi-Zaad & Salcudean, 2001), (Lawrence, 1993), etc. However, transparency focus on the communication characteristics of the master-slave system, the effect of environment property to operator's haptic performance is not considered. This limitation leads to some situations that the absolute transparency (although nonexistent) is not always an ideal operation condition, for example, when the target environment is very soft, an ideally transparent system will transmit only a soft feedback sensation back to the operator. Considering the environment property, a certain level of virtual stiffness applied in the system that degrades transparency can enhance task performance by preventing accidental damage to the target environment (O'Malley & Goldfarb, 2004). In some other cases, a certain level of system impedance that degrades transparency is needed if the excitation signals from the environment are not expected, (Misra & Okamura, 2006). In a word, an index that includes the influence of both the considerations on systematic and environment property is needed.

In other researches, both the influence of systematic and environment parameters on operator's haptic performance are considered. Christiansson et al. quantified the influence of stiffness and damping on object discrimination during grasping in a size-discrimination task (Christiansson, Van Der Linde, & Van Der Helm, 2008), but this index is for specific operations. The contact between the slave device and the environment, which is extensively existed in mater-slave system operation, was not focused.

"Rate-hardness" is an index proposed to quantify the operator's perception of the hardness of objects in using haptic interfaces when the contact between the slave device and the environment happens (Lawrence, Pao, Dougherty, Salada, & Pavlou, 2000), in which both the properties of the environment and the system is considered. However, if objects in the target environment are fragile like soft tissue in surgical applications, how easily with which an operator can sense the contact between the slave device and the environment, is more important than the perception of environment property.

Son et al. proposed a perception-based method for haptic teleoperation systems (Son, Cho, Bhattacharjee, Jung, & Lee, 2014). They proposed a perceptual index defined as a combination of quantified detection and discrimination abilities. With this index, the operator's contact detection ability can be assessed, however, the relationship between detection ability and the parameters is not derived, when applying this index in system parameter adjustment, a lot of preparation work such as plotting a graph of perception region is needed, and a specialized knowledge of control theory is required to the executant. Hence, the perceptual index are not practical to use in parameter adjustment in the field, the parameter optimization must be done before the system is deployed.

Many auxiliary devices such as approaching sensors can be used to prevent the slave device from invading the environment too much, but in cases that device size, sanitation, or cost are important limits, the haptic performance of contact detecting must be controlled with adjustments to systematic parameters.

Therefore, in tasks that operator's sensation of the contact between slave device and the environment is important, an index that satisfies the following two requirements is needed. First, the index should assess the operator's contact sensation with considering the systematic parameters as well as the environment property. Second, the index should to be easily used in system parameter adjustment in the field. To the best of our knowledge, no other study has addressed this problem, and the systematic parameters are still optimized with trial-and-error adjustment.

1.2. Objective and organization

Therefore, we aim at proposing a new index to estimate the operator's haptic sensation of the contact which can satisfy the requirements above. Firstly, we derive the index from the motion factor of device, since the device's motion factors after contact are determined by both the systematic and the environment parameters, both the influence of them can be represented on the index value, the first requirement is satisfied. Secondly, we relate this index value quantitatively to the system and environment parameters, by which the effect of adjusting system parameters can be reflected on the index value. Parameter adjustment can be conducted just using the quantitative relationship without other expertise, parameter adjustment will become clear and direct. The second requirement is satisfied.

This paper mainly introduces the first step of this research, i.e., proposing an index to estimate the operator's haptic sensation. The structure of this paper is as follows. Section 2 outlines our proposal for the haptic sensation index. Section 3 reports experiments that study two characteristics of our proposal, and in Section 4, the validity of the proposed index is demonstrated with another psychophysics experiment.

2. Proposal for the haptic sensation index

When the slave device contacts the environment, the motion of both the master and slave devices will change due to the bilateral control. During operation of the master–slave system, we assume that the operator's fingers are always clinging to the master device, thus the dynamic factor of the master device will provide the stimuli that generate haptic sensation. Undoubtedly, the master's dynamic factor is correlated with the systematic parameters, thus the relationship between intensity of the haptic sensation stimuli and the systematic parameters can be derived. Using the derived relationship, the stimuli intensity can be calculated as an index value.

Although the individual variance exists, degree of operator' haptic sensation is determined by the stimuli intensity. Hence, the index value can be used to estimate the operator's haptic sensation in an average and general level. As it is derived from the dynamic factor before and after contact, we call this index as dynamic contrast *C*.

It is noteworthy that the index is used to estimate the operator's haptic sensation at a general level, not to indicate the accurate sensation level for a given operator or every contact.

2.1. Dynamic factors in contact sensing

Based on the intensity of the feedback, different modalities of haptic sensations are used. If the feedback is weak, contact is sensed by cutaneous sensation. The cutaneous receptors under the finger pads work for such sensations. Tan et al. studied the detection and discrimination ability for finger-pad and claimed that the firing of these receptors is a function of the mechanical work exchange in a cutaneous interaction (Tan, Durlach, Beauregard, & Srinivasan, 1995). The firing rate of cutaneous receptors (FA and SA receptors) is functions of the skin curvature's changing speed (Dahiya, Metta, Valle, & Sandini, 2010).

If the feedback is intense, kinesthetic sensations from changes in the operator's wrist and arm positions will dominate the sensing of contact. From the review literature on kinesthetic sensation (Jones, 2000) and a study of the kinesthetic sensation in haptic feedback generated by a motor (Jones & Hunter, 1990, 1993), kinesthetic sensation are believed to be sensed by the primary spindle receptors in the arm muscles. The acceleration and velocity of the arm and wrist joints are coded by the primary spindle receptors to generate a sensation of contact.

Unlike visual and olfactory stimuli, for which people can easily distinguish a difference in modality, the border between cutaneous and kinesthetic sensations is unclear to a subject. Studies have testified that a combination of kinesthetic and cutaneous feedback improves teleoperator performance over the performance possible with cutaneous feedback alone (Pacchierotti, 2015). Haptic-feedback devices are, therefore, usually designed to combine these two types of sensations (Wei, Zhou, Nahavandi, & Wang, 2016).

If we wish to measure a dynamic factor of the master-slave system that most easily tracks the operator's haptic sensation, that factor should be existed in both cutaneous and kinesthetic sensing. Based on the analysis above, we hypothesize that the change extent on master device velocity before and after contact will effectively match with the stimuli that provide the operator with contact sensation.

2.2. Calculation of the index value

Figure 1 plots some examples of the master device's velocity profile before and after contact. As shown in the figure, if the velocity of the master device drops smoothly after contact

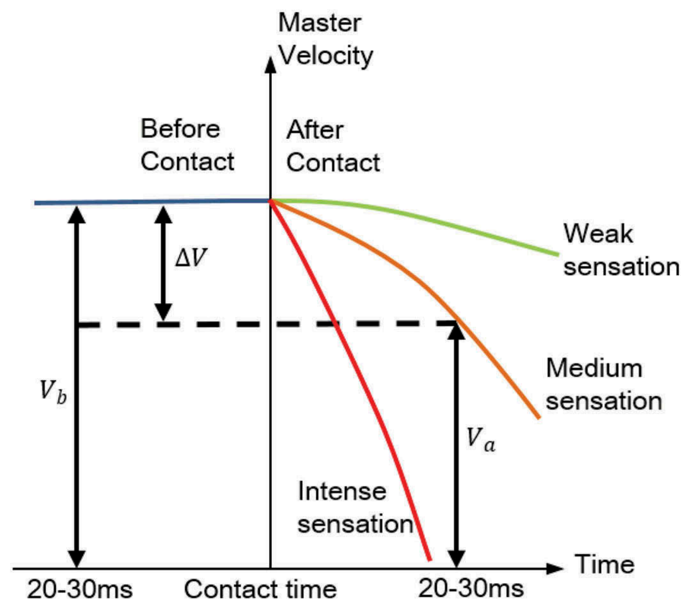


Figure 1. Examples of master device velocity profiles. The sharpness in the change in velocity is hypothesized to be functionally related to the operator's haptic sensation.

with the environment, the operator will be difficult to sense the contact. If the velocity of the master device reduces suddenly, it will be very easy for the operator to sense the contact. We treat the ratio of master-device velocity before and after contact as the factor that determines the stimuli of operator's haptic sensation. Thus the proposed index can be calculated as:

$$C = 1 - \bar{V}_a / \bar{V}_b \quad (1)$$

In equation (1), V_b and V_a are the velocities of the master device before and after contact, respectively. According to equation (1), if the master device's velocity does not change, no contact sensation is provided ($C = 0$); if the master device comes to a full stop immediately after contact, the operator's contact sensation is very strong ($C = 1$). The index value lies within the range [0, 1] and has no dimensions.

When calculating the *C* value, the average master velocities over the 50 ms before and after contact are used. This is supported by several considerations. First, the master velocity used in this calculation is not expected to be affected by the active muscle motion of the operator. According to (Gillespie & Cutkosky, 1996), the time duration should be set to 30 ms to preclude volitional control; second, if the feedback is weak, the feedback can be looked upon as a vibration at low frequency. According to human haptic mechanism, the sensation of low-frequency vibration is generated by the FA1 receptor (Meissner corpuscles), temporal resolution of which ranges from 15 to 50 ms (Abraira & Ginty, 2013). If the feedback is relatively intense, kinesthetic sensation dominates haptic sensation, of which the temporal resolution has been measured in the range 17–35 ms (Bhardwaj & Chaudhur, 2015). Averaging the velocity over 50 ms represents the velocity within 20–30 ms of the relevant sensation modalities' temporal resolution. With these factors in mind, we chose to average the master-device velocity for 50 ms before and after the moment of slave contact with the environment.

3. Characterization of the haptic sensation index

In this section, characteristics of the proposed index are studied, including the statistical characteristics and the necessary change ratio to an index *C* value to produce a just noticeable different haptic sensation.

3.1. Experimental apparatus

We built a master–slave system with impedance adjusting bilateral control diagrammed in Figure 2. The master side is the Phantom Desktop haptic device (SensAble Technologies, Woburn, Massachusetts State, USA). To allow an ideal system without interference from mechanical factors, the slave side and the operational environment are modeled in a virtual world; the slave side is a virtual sphere and the operation environment is a virtual wall. The update rate of the system is fixed at 1 kHz.

The definitions and units of each parameter in Figure 2 are as follows:

B_m: Damping of the master device, (Ns/mm);
K_s: Stiffness between master and slave, (N/mm);
B_s: Damping between master and slave, (Ns/mm);
K_{en}: Stiffness of the virtual wall, (N/mm);
f_h: Force applied by the operator, (N);
f_{en}: Force applied by the environment (virtual wall), (N).

The equations of motion for the system in Figure 2 are

$$f_h = M_m \ddot{r}_m + B_m \dot{r}_m + K_s(r_m - r_s) + B_s(\dot{r}_m - \dot{r}_s) \quad (2)$$

$$f_{en} = K_{en}(r_s - r_{wall}) = M_s \ddot{r}_s + K_s(r_s - r_m) + B_s(\dot{r}_s - \dot{r}_m) \quad (3)$$

In equations (2) and (3), r_m is the position of the master device, r_s is the position of the slave sphere, and r_{wall} is the position of the virtual wall, which is constant. For simplicity, only the stiffness of the wall is represented as the properties of the environment.

In pilot studies, we found that the damping of the master device B_m and the stiffness of the virtual wall K_{en} affected the operator's haptic sensation remarkably more than the other parameters. Hence, in psychophysics experiments, operator's haptic sensation for the contact were measured by adjusting the parameters B_m and K_{en}, and holding other system parameters constant.

3.2. Experimental methods

We enrolled 10 subjects, nine males and one female, all between 22 and 35 years old. All subjects were right-handed. The experiment was conducted in accordance with standard ethical practices and was approved by the ethics committee for human experiments of the Tokyo Institute of Technology.

Subjects performed the following motion in the experiments. As the master device moves forward, the slave sphere in the virtual world also moves forward and contacts with the virtual wall. The subject held the stylus of the master device in their right hand and moved the stylus forward at arbitrary speed (keep the velocity before contact constant is expected). The appearance of the experiment is shown in Figure 3. During the experiment, subjects could not see the motion on the slave side; all motions were judged solely by haptic sensation.

3.3. Experimental for statistical characteristics

3.3.1. Experiment objective

The contact velocity will vary considerably for different operators of a master-slave system. Therefore, under the same parameter combination, the extent to which the index value is affected by different operators or contact velocities should

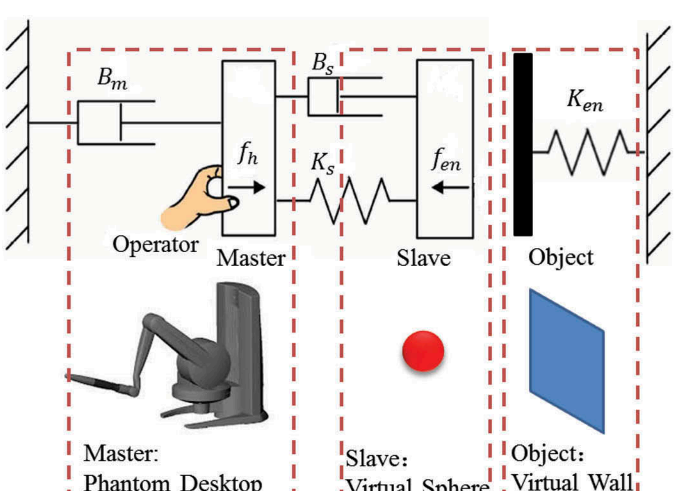


Figure 2. Control model and device of experiment system.
The master side is a haptic device: Phantom Desktop, slave side is a virtual sphere and the operating environment is a virtual wall.

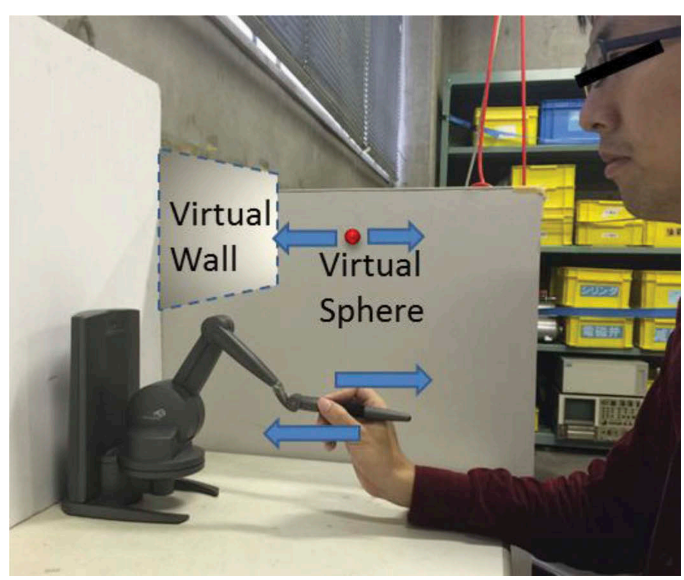


Figure 3. Appearance of the experiment.
Subjects are instructed to hold the stylus, perform approach-retract movement, and remember the haptic sensation when the slave sphere contacts the virtual wall.

be studied. To clarify this property, the statistical characteristics of the index value with different operators were studied.

3.3.2. Experimental procedures and results

The 10 subjects mentioned in Section 3.2 performed experiments with the master-slave system. In this experiment, we tested the 10 parameter combinations listed in column 2 of Table 2. For each parameter combination, the 10 subjects were instructed to repeat the approach-retract motion 10 times, consciously varying the speed with which they approached the target wall over the 10 trials. The velocity profiles from every trial were recorded, so we get 100 index values for each parameter combination. The 100 calculated index values are distributed normally according to the Kolmogorov-Smirnov normality test. As an example, histograms that count each index value for cases 1 to 4 are shown in Figure 4. Although these 100 calculated index values are not entirely independent, the subjects were instructed to consciously change the approach velocity for each of the 10 contacts they performed for each set of parameters. If we don't associate each subject's 10 approaches for each parameter set together, the 100 time contacts for each parameter set are sufficiently independent for our purposes.

For all 10 parameter combinations, the mean, standard deviation, and coefficient of variation of the 100 index values calculated from the recorded velocity profile are listed in Table 2. All coefficients of variation are under 15% except for cases 1 and 6. According to Reed, Lynn, & Meade (2002), a coefficient of variation less than 15% indicates that the index value will not diverge to an unacceptable level. Therefore, under different operators and different contact velocity, variation of the index value is within an acceptable range.

We also found that the value of *C* is independent of the approach velocity. Figure 5 shows an example of velocity profiles measured with different approach velocities under the parameter combination of case 4. If we use equation (1) to calculate the index value for each velocity profile, the results are the nearly the same.

For all the parameter combinations tested in the experiment, the approach velocities applied by the subjects varied from 50 to 350 mm/s. The correlation between the index values and the approach velocity was tested; the probability of the null

Table 2. Statistical characteristics of *C* measurements.

CASE	Parameter Combination	Sample Size	Mean value of C	Standard Deviation	Coefficient of Variation
1	B_m= 0.001, K_{en} = 0.1	100	0.149	0.027	18.1%
2	B_m= 0.001, K_{en}= 0.2	100	0.243	0.032	13.2%
3	B_m= 0.001, K_{en}= 0.3	100	0.365	0.045	12.3%
4	B_m= 0.001, K_{en}= 0.4	100	0.449	0.044	9.8%
5	B_m= 0.001, K_{en}= 0.5	100	0.501	0.054	10.7%
6	B_m= 0.004, K_{en}= 0.1	100	0.119	0.022	18.4%
7	B_m= 0.004, K_{en}= 0.2	100	0.202	0.028	13.8%
8	B_m= 0.004, K_{en}= 0.3	100	0.305	0.032	10.4%
9	B_m= 0.004, K_{en}= 0.4	100	0.384	0.036	9.4%
10	B_m= 0.004, K_{en}= 0.5	100	0.460	0.047	10.2%

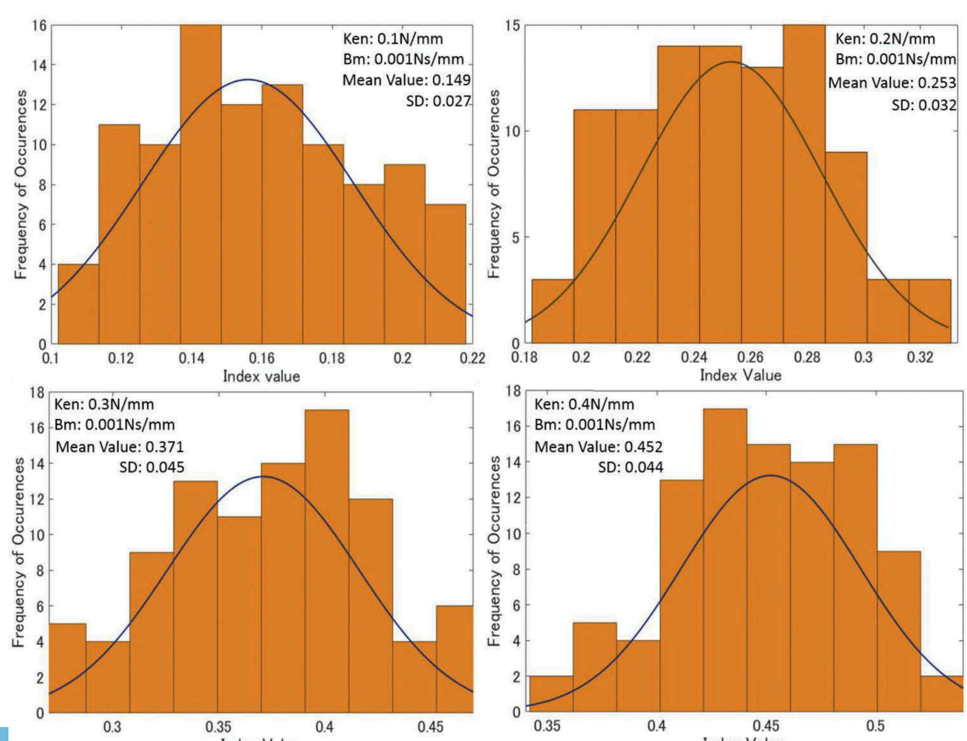


Figure 4. Distribution of index value.
Histograms of the index value measured in 100 trials with the parameter combinations in cases 1 to 4. The index measurements are normally distributed.

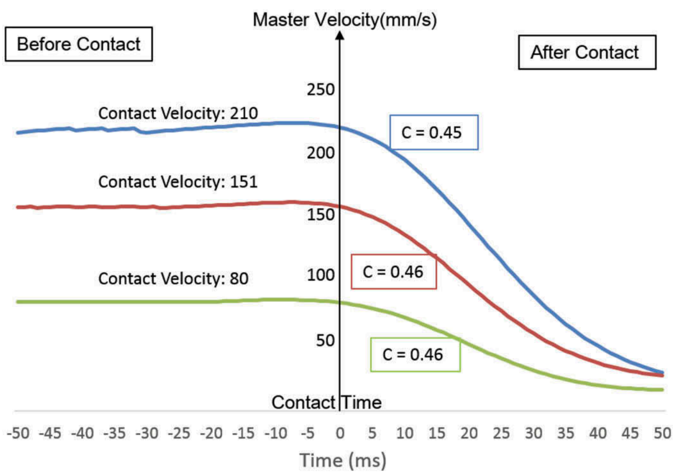


Figure 5. Examples of velocity profiles with different approach velocities under the same parameter combination, using the velocity profiles to calculate the index value, the results are the nearly the same.

hypothesis (that the *C* value is not correlated with approach velocity) was set to 0.05. The statistical significance *p* of the correlation between the approach velocity and *C* changes from 0.35 to 0.48 and the correlation coefficient ranges from 0.155 to 0.531, which means the *C* value is unlikely to depend on the approach velocity except in case of extreme approach velocities. Here, the relationship between approach velocity and the *C* value is discussed, the relationship between approach velocity and the true haptic sensation will be discussed in Section 5.

3.4. Experiment for reflecting the jnd of haptic sensation in the index value

3.4.1. Objective

While adjusting system parameters for some requirements, how the operator's haptic sensation for the contact will be changed after adjusting the parameters should be estimated. Among many kinds of changes, the simplest and most basic are strengthening and weakening effects. Therefore, we implemented a psychophysics experiments to study the how a strengthening or weakening to the operator's haptic sensation is reflected on the index value.

We measured the just-noticeable difference (JND) against designated 10 references haptic sensations, in both strengthen and weaken direction. Then, change in the index value between the JND and reference haptic sensations can be calculated.

The reference haptic sensations are generated from the stimuli under 10 reference parameter combinations (Cases 1–10 in Table 2). The JND is divided into an upper threshold (UT: the reference sensation is strengthened until the difference can be just noticed) and lower threshold (LT: the reference sensation is weakened until the difference can be noticed). Therefore, 20 JNDs are measured in total for 10 reference haptic sensations.

3.4.2. Experimental procedure

Ten subjects performing the experiment in Section 3.3 were also used in this experiment, in every trial, the subject repeated this approach-retract motion for successively five times, just like knocking on a door. The experiment is designed based on the up-and-down method for testing JNDs. This method is used extensively in psychophysics studies (Jones, 2013).

A reference trial and a comparison trial were conducted as one set. Both the two trials were presented to the subject, and the subject was asked whether they noticed a difference in the easiness of detecting the contact with the environment in the two trials. To prevent time error, we alternated the presentation of reference and comparison trials in a random order.

To illustrate this experiment in detail, we next introduce the process for obtaining the UT sensation to the reference sensation under parameter combination Case 1 (K_{en}: 0.1 N/mm, B_m: 0.001 Ns/mm); this process is also illustrated in Figure 6. In the reference trials, the parameter combination was constant. In comparison trials, B_m was kept constant and K_{en} began at 0.3 N/mm, which is far higher than the reference trial of 0.1 N/mm, allowing the subjects to easily notice the difference between the reference and comparison trial and answer "Yes."

As long as the subjects noticed a difference in haptic sensation between the comparison and reference sensation, we reduced K_{en} in the comparison trials by increments of 0.01 N/mm to approach the K_{en} in reference parameter combination (0.1) gradually until the subject could no longer detect a difference between the comparison and reference sensation. The subject in the example in Figure 6 could no longer detect the difference when K_{en} was reduced to 0.13 N/mm in the comparison trial, answering "No."

When the difference between reference and comparison sensations disappears, we increased the K_{en} in comparison trials with increments of 0.01 N/mm until the subject could again notice a difference in haptic sensation between the comparison and reference. In the example of Figure 6, this answer "Yes" reappeared at K_{en} = 0.16 N/mm.

The ascending and descending series were repeated twice each, and we recorded the K_{en} values at which the difference between reference and comparison emerges or disappears

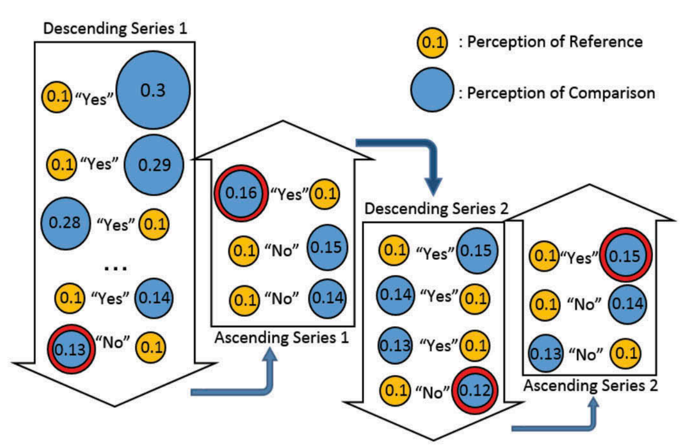


Figure 6. Process for measuring the just-noticeable different haptic sensation with the reference sensation (environmental stiffness K_{en}= 0.1 N/mm). Descending and ascending series of trials are presented, and altered until a difference emerges or disappears. Haptic sensations are represented by the circle size. "Yes" or "No" between two circles are the subject's answer of whether a difference between the comparison and the reference sensation can be noticed. Circles with red rings are the recorded K_{en}, at which the subject's perception of a difference in the stimuli appeared or disappeared.

(subjects answer transition between "Yes" and "No" occurred, for example, K_{en} = 0.13 N/mm, 0.16 N/mm, 0.12 N/mm, and 0.15 N/mm in Figure 6). The mean of the four recorded K_{en} values, 0.14 N/mm in this example, is the UT K_{en} parameter at which the upper difference in haptic sensation compared to the reference sensation is just noticeable. Velocity profiles with the reference and UT parameter combinations were also recorded, from which the corresponding index values can be calculated.

The process for measuring the LT was the same, but with reversed ascending and descending series in which the initial comparison K_{en} parameter was far lower than that the reference trial.

3.4.3. Experiment results

The LT and UT index values averaged from responses of the 10 subjects for every reference parameter combination are listed in Table 3. The sample size for the calculation of the reference *C* values (column 3) is 20, and is 10 for the calculation of UT (column 4) and LT (column 6) *C* values.

Columns 5 and 7 of Table 3 shows R_C, which is the ratio of index values between the reference and their corresponding JNDs of a difference in stiffness and the JND of transmitted stiffness. According to Table 3, as the reference index value (C_{ref}) increases, the R_C becomes noticeable decreases. We consider this situation appears because of the difference in haptic modalities. When the feedback is weak, the contact sensation is the cutaneous sensation; as it increases, the kinesthetic sensation will be involved, which sensitizing the discrimination ability.

In extreme cases, when the reference haptic sensation is estimated to be minimal ($C \rightarrow 0$), R_C approaches infinity. When the reference haptic sensation is estimated to be very intense ($C \rightarrow 1$), the haptic sensation is close to perceiving the environment stiffness, which has been studied previously Hirano, Maruyama, & Nakahara (2000) and Botturi, Vicentini, Righele, & Secchi (2010). These studies revealed that the difference threshold will be about 10 ~ 20% higher than the reference stimulus. Therefore, in this research, we choose an intermediate value of R_C = 1.15 as the appropriate index change ratio when the reference is very intense.

Table 3. UT and LT K_{en} and the corresponding index value to 10 references.

No.	Reference Parameter Combination	Mean of Reference *C* value: C_{ref}	Mean of UT *C* value: C_{UT}	$R_c = C_{UT}/C_{ref}$	Mean of LT value: C_{LT}	$R_c = C_{ref}/C_{LT}$
1	B_m= 0.001, K_{en}= 0.1	0.149	0.212	1.423	0.087	1.712
2	B_m= 0.001, K_{en}= 0.2	0.243	0.340	1.399	0.165	1.447
3	B_m= 0.001, K_{en}= 0.3	0.365	0.456	1.249	0.253	1.445
4	B_m= 0.001, K_{en}= 0.4	0.449	0.530	1.180	0.300	1.496
5	B_m= 0.001, K_{en}= 0.5	0.501	0.610	1.220	0.361	1.385
6	B_m= 0.004, K_{en}= 0.1	0.119	0.185	1.554	0.073	1.630
7	B_m= 0.004, K_{en}= 0.2	0.202	0.314	1.554	0.138	1.463
8	B_m= 0.004, K_{en}= 0.3	0.305	0.445	1.459	0.203	1.525
9	B_m= 0.004, K_{en}= 0.4	0.384	0.480	1.250	0.263	1.460
10	B_m= 0.004, K_{en}= 0.5	0.460	0.552	1.196	0.341	1.353

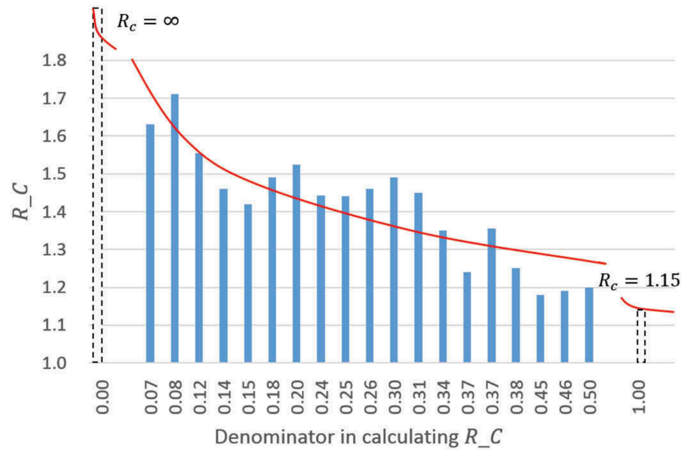


Figure 7. Reference *C* values and R_C, the necessary change ratio R_C to a reference *C* value to make the difference between two haptic sensations noticeable, including extreme cases.

In trials of UT measurement, $R_C = C_{UT}/C_{ref}$; and in trials of LT measurement, $R_C = C_{ref}/C_{LT}$, we plot all the denominators in calculating R_C on the horizontal axis (including the extreme cases in which C_{ref} = 0 and 1), and the R_C value on the vertical axis in Figure 7. This plot allows us to calculate the necessary change extent to a reference index value *C* that will produce a JND in the operator's haptic sensation.

According to Figure 7, the R_C and reference *C* (C_{ref}) values can be fit to the following logarithmic function:

$$R_C = \log_{0.001}^{C_{ref}} + 1.15 \quad C_{ref} \in [0, 1] \tag{4}$$

If C_{ref} is close to 1.0, to make a different sensation, $C = C_{ref} \times R_C$ is larger than 1.0; this situation only arises when the master device bounces unstably faster than the temporal resolution of haptic sensation.

4. Validation of the haptic sensation index

The final goal of this research is to guide the parameter adjustment directly from the index values, if the index value can estimate the operator's haptic sensation correctly, regardless of how the parameters are adjusted, haptic sensations they provide to the operator can be estimated as long as their *C* values is determined.

Therefore, despite the difference in parameters combination of trials, as well as the relationship of their corresponding values is known, the operator's performance in haptic sensation should be in accordance with prediction that based on the index values. In this section, another psychophysics experiment was conducted, in which we tested pairs of parameter combinations with designated relationships of *C* value between the pair elements, presented the sensations under the designated parameter combination pairs to the subjects and checked if their haptic sensation performances were in accordance with the prediction.

4.1. Relationship between parameters and *C* value

To best adjust parameters to desired *C* values, we studied the relationship between parameters and the index value preliminarily. Figure 8 plots all the reference, UT, and LT *C* values against the corresponding parameter combinations that were discussed in Section 3.4.3. Then, we fit the functions of K_{en} and the index value: $C = f(K_{en})$ for the two levels of master damping B_m with the following equations:

$$C_{Bm0.001} = 1 - \exp(-1.355 \cdot K_{en}) \quad (5)$$

$$C_{Bm0.004} = 1 - \exp(-1.211 \cdot K_{en}) \quad (6)$$

The coefficients of determination for the two fitted curves are 0.987 and 0.990, respectively.

4.2. Experimental apparatus, subjects, and task

The experimental apparatus was the same as that used in the previous experiment. We enrolled 15 subjects, all males from 22 to 35 years old. The subjects performed the same motion described in Section 3.2.

4.3. Experimental procedure

The experiment was based on the method of constant stimuli. Sensations from two system parameter combinations were presented in a pair with a time interval less than 0.5 s. After presenting one pair, the subject was asked to identify the trial in which they could more easily to sense the contact between the slave and the environment. Subjects could answer "Former," "Latter," or "Same."

The designated relationships between index values for pairs of parameter combinations were divided into three types: 1. parameter combinations with the same *C* value, 2. parameter combinations with just-noticeably-different *C* values, and 3. parameter combinations with *C* values differing by 200%. We tested five pairs of parameter combinations for the first two types and four parameter pairs for the third type, in which the pair elements are labeled A_1–A_5 and B_1–B_5.

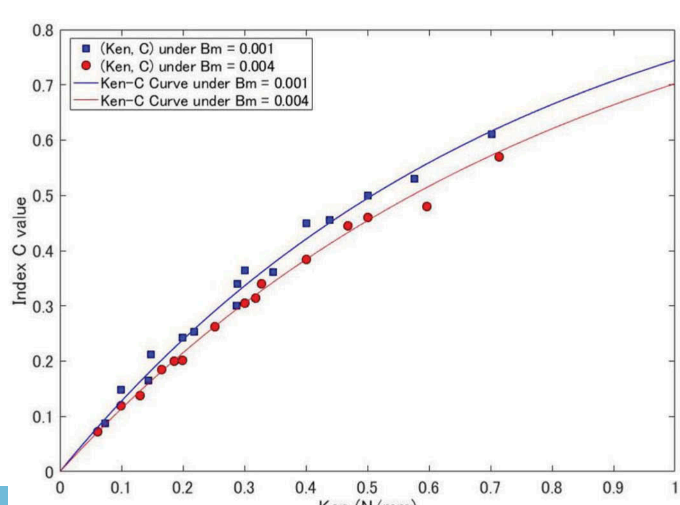


Figure 8. Parameter combinations and their corresponding *C* values as listed in Table 3. The curves are fitted functions for K_{en} and the index value.

For each subject, we repeated every pair of parameter combinations 20 times. Therefore, for each pair, 300 trials were tested in total. To eliminate constancy errors, the sequence of presenting pair elements was random. To prevent the subject from deducing answers from the ongoing statistics, parameter combination pairs with the three kind of relationships were presented in a random sequence.

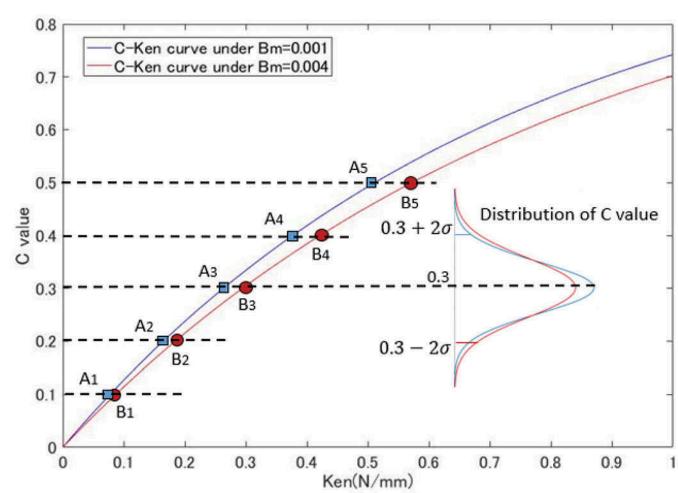
For each pair of parameter combinations, the proportion of indistinguishable answer was counted, which includes the proportion of "Same" answer and the proportion of opposite responses that canceled out with each other.

If the *C* values under the two pair elements were the same, the operator would be difficult to tell the difference on the haptic sensation, which will lead to a high proportion of indistinguishable answers. If the change rate of index values between pair elements reaches R_C, according to psychophysics theory, the proportion of indistinguishable answers should be around 50%; If the index values between pair elements differs by 200%, proportion of the indistinguishable answers should be very low.

4.4. Experimental results

4.4.1. Pairs of parameter combinations with equal C index values

Figure 9 shows the parameter pairs of which index C value pairs is designated as the same; the five appointed index *C* values of pair elements are shown in columns 3 and 5 of the table in Figure 9. Substituting the appointed index values and into equations (5) and (6) for different B_m levels, the K_{en} parameter in each pair element is back-calculated, respectively. Here, the K_{en} parameters in A_1-B_1 ~ A_5-B_5 are listed in columns 2 and 4 of the table in Figure 9.



No.	*Ken*(N/mm) in parameter set A	*C* value of A	*Ken*(N/mm) in parameter set B	*C* value of B
1	0.078	0.10	0.087	0.10
2	0.165	0.20	0.184	0.20
3	0.263	0.30	0.295	0.30
4	0.377	0.40	0.422	0.40
5	0.512	0.50	0.572	0.50

Figure 9. Five parameter combination pairs of type 1, for which the haptic sensation is expected to be same.

The combinations of system parameters with the same index *C* value are expected to present the same haptic sensation to the subjects. In this experiment, for each pair of parameter combinations, the proportion of indistinguishable answers after 300 trials is shown in Table 4. From this, we can see that the proportion of indistinguishable answers is high and nearly more than 80%.

However, "high proportion" or "more than 80%" are only independent results without any reference, they should be compared to a predicted proportion to check if the proportion is high enough to reflect the "same haptic sensation." To check whether haptic sensation performances were in accordance with the prediction. The third row of Table 4 is the predicted proportion of indistinguishable answers. Here, the algorithm is introduced as follows:

As mentioned in Section 3.3.2, the index value under a certain parameter combination are normal distribution, in Figure 9, points on the curves are the mean values of the normal distributions, and true index value in each trial may be different from the point values on the curves. For example, if the true index value when presenting A_3 in one trial was $0.3-2\sigma$ of the red distribution, whereas the true index value when presenting B_3 in another trial was $0.3+2\sigma$ of the blue distribution (see the example of normal distributions in Figure 9), in this pairwise comparison, the difference between the haptic sensation provided by A_3 and B_3 may be more than the just-noticeable threshold, which makes the subject to notice the difference.

In the pairwise comparison, pair element A is presented firstly, the true index value C_A under pair element A from all subjects $C_{A\_M}-2\sigma$, $C_{A_M}+2\sigma$are within the range $[C_{A\_M}-2\sigma, C_{A\_M}+2\sigma]$, then, pair element B is presented, the true index value C_B from all subjects are within the range $[C_{B\_M}-2\sigma, C_{B\_M}+2\sigma]$. Here, C_{A_M} and C_{B_M} are the mean index value under pair element A and B, respectively. If C_B is within the range $[C_A/R_C, C_A/R_C]$, haptic sensation difference between the pair element A and B is estimated to not beyond the JND, the subject should not notice the difference.

Therefore, proportion of the indistinguishable answers is "The chance for the true index value of element B (C_B) being within the difference unnoticeable range of element A's true index value: $[C_A/R_C, C_A/R_C]$," which can be calculated by the following convolution integral.

$$p=\int_{C_{A\_M}-2\sigma}^{C_{A\_M}+2\sigma}\left\{\int_{C_A}^{C_A+\Delta C_A} f_A(C)dC\cdot\int_{C_A/R_C}^{C_A\cdot R_C} f_B(C)dC\right\}dC \qquad (7)$$

In equation (7), p is the proportion of the indistinguishable answers, C represents the true index value of current pair element, $f_A(C)$ and $f_B(C)$ are the probability-density functions of the normal distributions of pair elements A and B. R_C can be calculated by substituting C_{A_M} into equation (4). For example, when calculating the expected proportion between A_2 and B_2, substitute the C_{A_M} value of A_2 (0.2) into equation (4), $R_C = 1.33$.

Comparing the experimental proportion of indistinguishable answer to the prediction proportion, we can say that the haptic sensation performances were in accordance with the prediction based on index relationship.

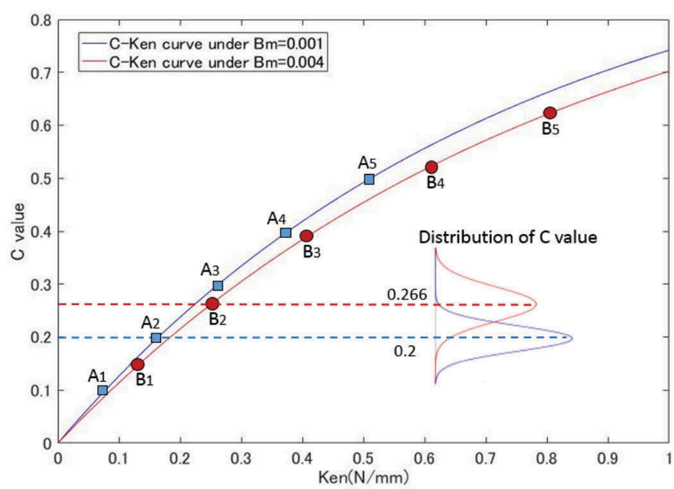
Table 4. Proportion of indistinguishable answers under the same *C* value, sample size of sample size of every pair is 300.

Parameter pair No.	proportion of Indistinguishable Answers	Predicted Proportion of Indistinguishable Answers
A_1, B_1	78%	71.1%
A_2, B_2	82%	81.3%
A_3, B_3	80%	86.9%
A_4, B_4	83%	87.2%
A_5, B_5	84%	87.5%

4.4.2. Pairs of parameter combinations with just-noticeably-different C values

Figure 10 shows the parameter combination pairs of which the *C* value difference between pair elements are designated as reaching the JND. The five designated index *C* value pairs are shown in the columns 3 and 5 of the table in Figure 10. The K_{en} parameter in A_1-B_1 to A_5-B_5 is listed in column 2 and 4 of the table in Figure 10.

According to psychophysics theory, the proportion of indistinguishable answers should be 50%. Considering the variance of true index value, the predicted proportions of indistinguishable answers calculated by equation (7) are about 47%. The experimental result is shown in Table 5.



No.	*Ken*(N/mm) in parameter set A	*C* value of A	*Ken*(N/mm) in parameter set B	*C* value of B
1	0.078	0.1	0.132	0.148
2	0.165	0.2	0.266	0.276
3	0.263	0.3	0.416	0.396
4	0.377	0.4	0.592	0.512
5	0.512	0.5	0.801	0.625

Figure 10. Five parameter combination pairs of type 2, for which the haptic sensation is expected to be just noticeable.

Table 5. Proportion of indistinguishable answers under the just noticeably different *C* value, sample size of every pair is 300.

Parameter pair No.	proportion of Indistinguishable Answers	Predicted Proportion of Indistinguishable Answers
A_1, B_1	44%	46.3%
A_2, B_2	40%	47.6%
A_3, B_3	41%	47.6%
A_4, B_4	46%	47.6%
A_5, B_5	45%	47.5%

From Table 5, when the difference ratio between the *C* values of the two parameter combinations reaches R_C, the proportion of indistinguishable answers is near the prediction. Haptic sensation performances were in accordance with the prediction based on index relationship.

4.4.3. Pairs of parameter combinations for which index values differ by 200%

Figure 11 shows the parameter combination pairs of which the index values of pair elements differ by 200%. The four designated index *C* values are shown in the columns 3 and 5 of the table in Figure 11. The K_{en} parameter in A_1-B_1 to A_4-B_4 is listed in columns 2 and 4 of the table in Figure 11.

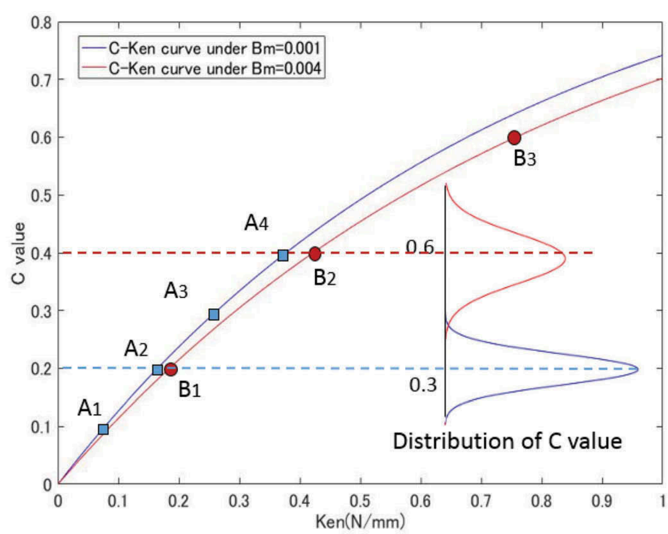
The proportion of indistinguishable answers for each pair out of 300 trails, as well as the predicted proportion calculated by equation (7), are shown in Table 6. From Table 6, when the change rate between pair element's index *C* values reaches 200%, proportion of indistinguishable answers becomes less than 5% of 300 trails. Haptic sensation performances were in accordance with the prediction based on index relationship.

4.4.4. Confirmation of the *effect of the master damping* B_m *on index C value*

In the above experiments, change on operator's haptic sensation is generated from the K_{en} parameter adjustment, but other systematic parameter can also affect haptic sensation. To confirm the effect of master damping parameter B_m, another type of parameter combination pairs was designated as follows: difference between the K_{en} parameters of pair element A and B reaches the upper threshold, but the B_m parameter values are adjusted to make the index value *C* of pair elements equal. The parameter combination pairs and their index *C* values are shown in the table included with Figure 12.

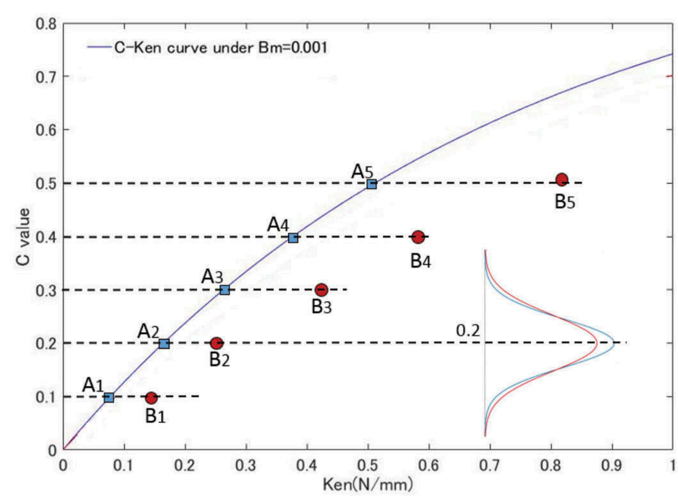
If the masking effect of master damping parameter B_m can also be represented by the index *C* value, subjects should not be able to distinguish the difference in haptic sensation even the difference of K_{en} parameter is large.

The proportion of indistinguishable answers for each pair out of 300 trials as well as the prediction are listed in Table 7. Haptic sensation performances were also in accordance with the prediction based on index relationship. According to the experimental results of Section 4, the proposed index value



No.	Ken(N/mm) in parameter set A	C value of A	Ken(N/mm) in parameter set B	C value of B
1	0.078	0.10	0.184	0.20
2	0.165	0.20	0.421	0.40
3	0.263	0.30	0.756	0.60
4	0.377	0.40	1.32	0.80

Figure 11. Four parameter combination pairs of Type 3, for which the haptic sensation is expected to be distinctly different.



No.	Parameter set A	C value of A	Parameter set B	C value of B
1	K_{en}: 0.078, B_m: 0.001	0.10	K_{en}: 0.132, B_m: 0.008	0.10
2	K_{en}: 0.165, B_m: 0.001	0.20	K_{en}: 0.266, B_m: 0.0085	0.20
3	K_{en}: 0.263, B_m: 0.001	0.30	K_{en}: 0.416, B_m: 0.0095	0.30
4	K_{en}: 0.377, B_m: 0.001	0.40	K_{en}: 0.592, B_m: 0.01	0.40
5	K_{en}: 0.512, B_m: 0.001	0.50	K_{en}: 0.801, B_m: 0.01	0.50

Figure 12. Five parameter combination pairs of type 4, for which the haptic sensation is expected to be the same while the difference on the K_{en} parameters between the pair elements reaches the upper threshold.

Table 6. Proportion of indistinguishable answers with distinctly different *C* values with sample size of every pair is 300.

Parameter pair No.	proportion of Indistinguishable Answers	Predicted Proportion of Indistinguishable Answers
A_1, B_1	12%	11%
A_2, B_2	3%	2%
A_3, B_3	6%	0%
A_4, B_4	3%	0%

Table 7. Proportion of indistinguishable answers with distinctly different K_{en} and the same *C* value; sample size of every pair is 300.

Parameter pair No.	proportion of Indistinguishable Answers	Predicted Proportion of Indistinguishable Answers
A_1, B_1	76.3%	71.1%
A_2, B_2	91.3%	81.3%
A_3, B_3	82.1%	86.9%
A_4, B_4	80.0%	87.2%
A_5, B_5	82.4%	87.5%

can represent operator’s haptic sensation correctly. Validity of proposed index is testified.

5. Discussion

5.1. Force and velocity factors in contact sensation

The force and velocity factor applied by the master device are interrelated, and it is natural to consider the force applied on the operator’s hand before and after contact as the factor that determines the contact sensation stimuli, but a pilot study showed that force factor has less of an effect on the operator’s haptic sensation than velocity factor.

In the pilot study, we measured the just noticeable lower threshold (LT) to a reference haptic sensation by adjusting different kinds of parameter. The parameter combination for the reference trials was (K_{en} = 0.3 N/mm, B_m = 0.001 Ns/mm). Two types of comparison parameter combinations were designed, in one type, the K_{en} parameter was reduced, and in another type, the B_m parameter was increased. Ten subjects were enrolled in this study, and the motion in the experiment was the same as discussed above.

The measured two types of LT parameter combinations are shown in the first column of Table 8. In type 1 LT parameter combination, the K_{en} parameter was reduced to 0.22 N/mm, in type 2 LT parameter combination, the B_M parameter was increased to 0.006 Ns/mm. No matter what kind of parameter is adjusted, if the haptic sensation offered by the comparison trial is just noticeably different from the reference, change extent on the hypothesized dynamic factor should be the same.

The first hypothesized dynamic factor is the difference in feedback force before and after contact. The force difference in the reference trial is 0.974 N; in type 1 LT parameter combination, the force difference is 0.672N, change extent to the reference is 45%; in type 2 LT parameter combination, the force difference is 0.788N, change extent to the reference is 23%, change extent on the hypothesized dynamic factor in the two types of LT parameter combinations are totally different, which doesn’t meet the premise that mentioned above.

The second hypothesized dynamic factor is the ratio of feedback force before and after contact, as shown in column 6 of Table 8, change extent on the hypothesized dynamic factor in the two types of LT parameter combinations are also totally different.

The third hypothesized dynamic factor is the ratio of velocity before and after contact, as shown in column 8 of Table 8, change extent on the hypothesized dynamic factor in the two types of LT parameter combinations are almost same. Therefore, we can see that operators are likely to rely on velocity factor rather than the force factor to sense the contact between slave device and the environment. This choice of velocity factor is also in accord with the literature discussed in Section 2. Furthermore, for convenience of using, we need to normalize the index value to a range of [0, 1], then, equation (1) is proposed as its definition.

5.2. Relationship between haptic sensation and approach velocity

In Section 3.3.2, the index value doesn’t depend on the approach velocity is testified. Here, the relationship between approach velocity and the operator’s haptic sensation will be discussed.

Firstly, the experimental participants tended to report that their approach velocity did not affect how easily they can sense the contact. Secondly, as mentioned in Section 2, the haptic sensation for sensing contact is generated from a combination of cutaneous and kinesthetic sensations. Hirano et al. (2000) and Srinivasan and Lamotte (1995) found that the approach velocity does not affect cutaneous sensation noticeably. As for kinesthetic sensations, Jones (2000) claims that the ability to detect a change in the position of a limb is not affected by the angular velocity of the arm movement, which is correlated with the approach velocity. Hence, the approach velocity is not likely to affect the operator’s contact sensation.

5.3. Application scope of the proposed index

In this paper, application scope of the index C is tasks that the force interaction between the slave and the environment, as well as the operator’s haptic performance on the force interaction are important. Typical application examples are surgery assistant system and nuclear operation.

As to the haptic tasks such as shape discrimination or texture recognizing, the important haptic performance will be the finger’s angle recognizing or vibration pattern discrimination, not the force interaction between the slave device and the environment. And as the title, the index C value can be calculated when the contact force between the slave device and the environment is fed back to the master side and of which the velocity profile is changed. In the master-slave systems without the force feedback function or systems that use other feedback strategies such as “sensory substitution”

Table 8. Change extent on the hypothesized indices in two types of LT parameter combination.

Parameter Combination	Sample Size	Factor 1 F_{after} - F_{before}	Change Extent	Factor 2 F_{after}/F_{before}	Change Extent	Factor 3 V_{before}/V_{after}	Change Extent
Reference K_{en}: 0.30 N/mm B_m: 0.001 Ns/mm	20	0.974	—	7.306	—	1.563	—
LT Type 1: K_{en}: 0.22 N/mm B_m: 0.001 Ns/mm	10	0.672	45%	5.754	27%	1.201	30%
LT Type 2: K_{en}: 0.30 N/mm B_m: 0.006 Ns/mm	10	0.788	23%	2.287	320%	1.185	32%

and "sensory subtraction" (Pacchierotti, Prattichizzo, & Kuchenbecker, 2016), the value of index C cannot be calculated. These kind of tasks are not in the application scope of the index C, other performance metrics should be used.

5.4. Application of the index

Our next step is to write the relationship between the index C and various systematic parameters as a function, from which the index value can be calculated from a combination of parameters.

$$C = f(\text{parameter1}, \text{parameter2}, \text{parameter3}\ldots) \quad (8)$$

Equation (8) is expected to guide parameter design. For example, while using a robot-assisted surgical systems to operate on delicate tissue, a surgeon may require high master damping to reduce hand vibrations, but the surgeon cannot allow the sensation of a contact between slave device and the tissue to dip below a critical value. The C value can be used to propose an adjustment to the other parameters that achieves this balance. First, the current parameter combination is substituted into equation (8) to determine C_1, which represents the intensity of current contact sensation stimuli. Second, substitute the damping parameter needed to mitigate hand vibrations into equation (8); the resulting index value C_2 represents the stimuli intensity under the new damping parameter, $C_1 > C_2$. If the difference between C_1 and C_2 is less than R_c, the adjustment to damping parameter is acceptable. If the difference between C_1 and C_2 is more than R_c, other system parameters can be adjusted in sequence until the contact sensation with the necessary damping adjustment matches the original contact sensation.

This example demonstrates how the index C can quantify and objectify parameter-adjustment processes that currently rely on trial-and-error.

6. Conclusions and future work

This article proposes an index for teleoperation systems can be used to estimate the haptic sensation for operators to sense the contact between slave devices and the environment.

First, we argued that the magnitude of the contrast in the velocity of master device before and after the slave device contact with the environment can be used to quantify the haptic sensation stimuli, and refer this performance index as dynamic contrast C.

Second, we used statistical analysis of psychophysics experiments result to show that the index value remains constant for different operators and is independent of the approach velocity applied by the operator. By measuring the JND in the haptic sensation by adjusting value of K_{en} and B_m, the necessary change ratio to a reference index C value to produce a just noticeable different haptic sensation was calculated.

Third, validity of the index was confirmed in psychophysics experiments. Results show that a change in haptic sensation can be represented by a change in the index C, regardless of how the parameters are adjusted to produce that C value. This correspondence between index values and subject's haptic performance implies that the value of C can represent the operator's haptic sensation correctly.

In the experiments of this paper, the adjusted parameters were only K_{en} and B_m because this two kinds of parameter affects the operator's haptic sensation most significantly in the device we studied. In many cases, the environment properties cannot be adjusted, and other system parameters will affect the operator's haptic sensation. Hence, in future works, more parameters such as the gains between the master and the slave, position scaling, and communication delay will be studied to fully formulate equation (8) and apply the proposed index to actual parameter design.

Acknowledgments

This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

ORCID

Dongbo Zhou http://orcid.org/0000-0001-8991-6207

References

Abraira, V., & Ginty, D. (2013). The sensory neurons of touch. *Neuron*, *79*(4), 618–639. doi:10.1016/j.neuron.2013.07.051

Beretta, E., Nessi, F., Ferrigno, G., & De Momi, E. (2015, September). *Haptic feedback enhancement for soft tissue interaction tasks in cooperative robotic surgery*. IEEE/RSJ International Conference on Intelligent Robots and Systems, Hamburg, Germany.

Bhardwaj, A., & Chaudhur, S. (2015, June) *Estimation of resolvability of user response in kinesthetic perception of jump discontinuities*. IEEE World Haptics Conference, Evanston, USA.

Bolopoin, A., & Regnier, S. (2013). A review of haptic feedback teleoperation systems for micromanipulation and micro assembly. *IEEE Transactions on Automation Science and Engineering*, *10*, 3.

Botturi, D., Vicentini, M., Righele, M., & Secchi, C. (2010). Perception-centric force scaling in bilateral teleoperation. *Mechatronics*, *20*(7), 802–811. doi:10.1016/j.mechatronics.2010.06.005

Christiansson, G. A. V., Van Der Linde, R. Q., & Van Der Helm, F. C. T. (2008). The influence of teleoperator stiffness and damping on object discrimination. *IEEE Transactions on Robotics*, *24*, 5. doi:10.1109/TRO.2008.2003274

Dahiya, R. S., Metta, G., Valle, M., & Sandini, G. (2010). Tactile sensing–from humans to humanoids. *IEEE Transactions on Robotics*, *26*(1), 1–20. doi:10.1109/TRO.2009.2033627

Gillespie, R., & Cutkosky, M. (1996, November) *Stable user-specific haptic rendering of the virtual wall*. Proceedings of the ASME International Mechanical Engineering Conference and Exhibition, *58*, 397–406.

Hashtrudi-Zaad, K., & Salcudean, S. (2001). Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulations. *International Journal of Robotics Research*, *20*(6), 419–445. doi:10.1177/02783640122067471

Hirano, M., Maruyama, T., & Nakahara, Y. (2000). Relationship between the recognition of object's hardness by human finger and contact force under various contact conditions. *Abstract of Dynamic & Design Conference*, *2000*, 370.

Jones, L. A. (2000).Kinesthetic Sensing. *In Human and Machine Haptics*. Cambridge, Massachusetts State: MIT Press.

Jones, L. A. (2013). Application of psychophysical techniques to haptic research. *IEEE Transactions on Haptics*, *6*(3), 268–287. doi:10.1109/TOH.2012.74

Jones, L. A., & Hunter, I. W. (1990). A perceptual analysis of stiffness. *Experimental Brain Research*, *79*(1), 150–156. doi:10.1007/BF00228884
Jones, L. A., & Hunter, I. W. (1993). A perceptual analysis of viscosity. *Experimental Brain Research*, *94*(2), 343–351. doi:10.1007/BF00230304
Kuiper, R. J., Frumau, J. C. L., Van Der Helm, F. C. T., & Abbink, D. A. (2013, October). Haptic Support for bi-manual control of a suspended grab for deep-sea excavation. UK: IEEE International Conference on Systems, Man, and Cybernetics, Manchester.
Lawrence, D. (1993). Stability and transparency in bilateral teleoperation. *IEEE Transactions on Robotics and Automation*, *9*(5), 624–637. doi:10.1109/70.258054
Lawrence, D. A., Pao, L. Y., Dougherty, A. M., Salada, M. A., & Pavlou, Y. (2000). Rate-hardness: A new performance metric for haptic interfaces. *IEEE Transactions on Robotics and Automation*, *16*(4), 357–371. doi:10.1109/70.864228
Misra, S., & Okamura, A. M. (2006, March). *Environment parameter estimation during bilateral telemanipulation*. Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Virginia, USA.
O'Malley, M. K., & Goldfarb, M. (2004). The effect of virtual surface stiffness on the haptic perception of detail. *IEEE/ASME Transections on Mechatronics*, *9*, 2.
Pacchierotti, C. (2015). Cutaneous & kinesthetic cues to improve transparency in teleoperation. In *Cutaneous haptic feedback in robotic teleoperation* (pp. 93–120). Cham, Switzerland: Springer.
Pacchierotti, C., Prattichizzo, D., & Kuchenbecker, K. J. (2016). Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery. *IEEE Transactions on Biomedical Engineering*, *63*(2), 278–287. doi:10.1109/TBME.2015.2455932
Reed, G. F., Lynn, F., & Meade, B. D. (2002, November). Use of coefficient of variation in assessing variability of quantitative assays. *Clinical and Diagnostic Laboratory Immunology*, *9*(6), 1235–1239.
Son, H., Cho, J., Bhattacharjee, T., Jung, H., & Lee, D. (2014). Analytical and psychophysical comparison of bilateral teleoperators for enhanced perceptual performance. *IEEE Transactions on Industrial Electronics*, *61*(11), 6202–6212. doi:10.1109/TIE.2014.2314058
Srinivasan, M. A., & Lamotte, R. H. (1995). Tactual Discrimination of Softness. *Neurophysiology*, *73*, 1.
Tan, H., Durlach, N., Beauregard, G., & Srinivasan, M. (1995). Manual discrimination of compliance using active pinch gasp: The roles of force and work cues. *Perception & Psychophysics*, *57*(4), 495–510. doi:10.3758/BF03213075
Wagner, C., Stylopoulos, N., Jackson, P., & Howe, R. (2007). The benefit of haptic feedback in surgery: Examination of blunt dissection. *Presence: Teleoperators and Virtual Environments*, *16*(3), 252–262. doi:10.1162/pres.16.3.252
Wei, L., Zhou, H., Nahavandi, S., & Wang, D. (2016). Toward a future with human hands-like haptics. *IEEE System, Man, and Cybernetics Magazine*, *2*(1), 14–25. doi:10.1109/MSMC.2015.2497178
Wildenbeest, J. G. W., Abbink, D. A., Heemskerk, C. J. M., Van Der Helm, F. C. T., & Boessenkool, H. (2013). The impact of haptic feedback quality on the performance of teleoperated assembly tasks. *IEEE Transactions on Haptics*, *6*(2), 242–252. doi:10.1109/TOH.2012.19
Zotovic Stanisic, R., & Valera Fernandez, A. (2012). Adjusting the parameters of the mechanical impedance for velocity, impact and force control. *Robotica*, *30*, 583–597. doi:10.1017/S0263574711000725
Zotovic Stanisic, R., Valera Fernandez, A., & Garc´Ia Gil, P. J. (2005, July). *Impact and force control with switching between mechanical impedance parameters*. Proceeding of the 16th IFAC World congress, Prague, Czech Republic.

About the Authors

Dongbo Zhou received the ME degree from the University of Tsukuba, Japan, in 2011. He is currently working toward the PhD degree at the Tokyo Institute of Technology. His research interests include haptics and robotics. His current work focuses on the aspects of kinesthetic sensation in master-slave robot systems.

Kotaro Tadano received Dr. Eng. degrees in mechanical engineering from Tokyo Institute of Technology, Japan, in 2007. He is currently an Associate Professor at Tokyo Institute of Technology. His research interests include robotics, teleoperation, and pneumatic systems. He is a Member of the IEEE Robotics and Automation Society.