Quantification of Arm Kinesthetic Sense Using an Arm Motion Generator

Jae-Bok Song and Woong-Chul Chung

***Abstract*—The human response caused by the motion of an object grasped by a human operator is defined as an arm kinesthetic sense. Due to nonlinearity and ambiguity of human senses, there is no absolute standard for quantification of kinesthetic sense. In this research, a so-called two-dimensional (2-D) arm motion generator is developed to emulate various mechanical impedance, i.e., stiffness or damping, characteristics of a human arm. The words representing arm kinesthetic sense are selected and then the subject's satisfaction levels on these words for given impedance values are measured and processed by the semantic differential method and factor analysis. In addition, in order to reflect the individual differences of each subject in the arm kinesthetic sense, compensation for individual differences based on the neural network technique is proposed. Through this proposed algorithm, the human sensations to arm movements described qualitatively can be converted into engineering data ensuring objectivity, reproducibility, and universality. This database can be used to develop user-friendly products related to arm motion.**

***Index Terms*—Arm kinesthetic sense, arm motion generator, factor analysis, mechanical impedance, semantic differential method.**

I. Introduction

The study of human motion in a man–machine interface (MMI) system can be divided into two categories. The first is the research based on the information theory proposed to investigate performance of a human by Shannon and Weaver [1]. Fitts [2] proposed Fitts' law which represents human performance by measuring the movement time proportional to task difficulty. This law has been applied to various research efforts; modeling of human performance in MMI [3], enhancement of speed and accuracy for a teleoperation system [4], and human movement related to arm posture [5]. The second is the study of information transmission between an operator and a slave robot [6]. That is, an operator obtains the kinesthetic information through the master manipulator so that more realistic operations may be achieved. Some researchers have related posture and motion of a human limb to mechanical impedance composed of stiffness, damping, and inertia [7]–[9].

Much existing research has been focused on performance, e.g., speediness and accuracy, improvement of an MMI system using information on human motion. Thus, a human was regarded as a system, and human psychophysical response (or human sensation) was not considered properly. But a human experiences a kind of kinesthetic sense in response to the movement of the vehicle on which he rides or the object he manipulates. In the case of not only change in position, velocity, and acceleration but also addition of kinesthetic feedback to a human motion, nonlinear and ambiguous human response is induced. The operator's feeling may affect the tasks requiring accuracy. Some studies investigating the effect of human feeling on the human motion related to playing the violin were performed [10]. In this research they related the feelings on the words representing a timbre to three bowing parameters, e.g., bow force, speed and sounding point.

Many objects manipulated by the human arms are characterized by the mechanical impedance, which consists of mass, damping, and stiffness. Depending on the mechanical impedance values these products provide different responses or sensations to the human operators. Since most operators do not have the concept of mechanical impedance, they express their responses verbally, e.g., strong, oppressive, comfortable, heavy, etc., when they manipulate the objects. Therefore, it is necessary to relate the verbal expressions to the mechanical impedance when the operator's opinions are reflected on the product development.

In this research, the human psychophysical response caused by the motion of an object grasped by a human operator is defined as an arm kinesthetic sense. A so-called two-dimensional (2-D) arm motion generator (AMG) is developed, which combines two perpendicular linear motors to represent various mechanical impedance, i.e., stiffness and damping, characteristics of a human arm. The words representing the arm kinesthetic sense are selected and then the subject's satisfaction levels on these words for given impedance values are measured and processed by the semantic differential method and factor analysis.

In addition, in order to reflect the individual differences of each subject in the kinesthetic sense, compensation for individual differences based on the neural network technique is proposed. The main purpose of this research is to convert the human sensations in response to human motion described qualitatively into engineering data ensuring objectivity, reproducibility, and universality. This database may help develop user-friendly products related to arm motion.

Section II of this paper takes a close look at the hardware structure of the arm motion generator developed in this study, and Section III handles the experimental procedure. Sections IV and V deal with factor analysis and quantification of kinesthetic sense, respectively.

II. Arm Motion Generator

It is important in this research to measure and analyze the human response or sensation when one manipulates the objects with a wide range of impedance, i.e., stiffness and/or damping, characteristics. However, varying the impedance physically is very tedious, costly, and time demanding. Thus, it is necessary to have the impedance of the object change with ease. In this research, therefore, the so-called AMG is developed to implement such active impedance [11]. This device is capable of implementing 2-D plane motion, i.e., x and y axes, by combining two identical linear motors perpendicularly as shown in Fig. 1 in order to investigate the kinesthetic sense related to arm motion. A linear motor is identical to a rotary motor except that it consists of the moving and fixed parts instead of the rotor and stator in the rotary motor. Thus, the moving part of the linear motor moves in the linear fashion. In the AMG the fixed part of the upper motor is attached to the moving part of the lower motor. An operator grasps the lever attached to the moving part of the upper motor and produces an arbitrary 2-D motion by moving the lever in the xy plane.

Note in Fig. 1 that $m,\ k,$ and c are the original mass, stiffness, and damping, while $\Delta m,\ \Delta k,$ and Δc are the added mass, stiffness, and damping created by the motor force. That is, the total mass, stiffness, and damping are such that $M = m + \Delta m,\ K = k + \Delta k,$ and $C = c + \Delta c$, respectively. The method which generates $\Delta m,\ \Delta k,\ \Delta c$, and thus, varies the mechanical impedance by the appropriate motor control, is called the active impedance technique. Implementation of active impedance means getting the same effect from physically changing the impedance of the moving part of the linear motor via generating the proper force from the motor.

Fig. 2 shows the systematic diagram of the AMG system. The digital signal processor (DSP) carries out the communication between the motor controller and the PC, measurement of the kinesthetic sense, and design of desired motion patterns. The TMS320C32 DSP board is used to control the motor. It receives the signals from the encoders measuring

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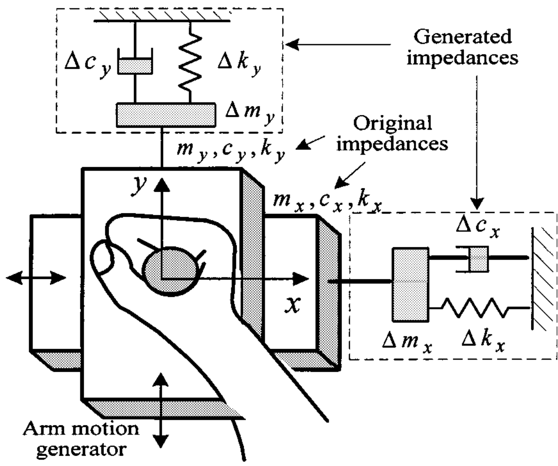

Fig. 1. Two-dimensional motion generator and its modeling.

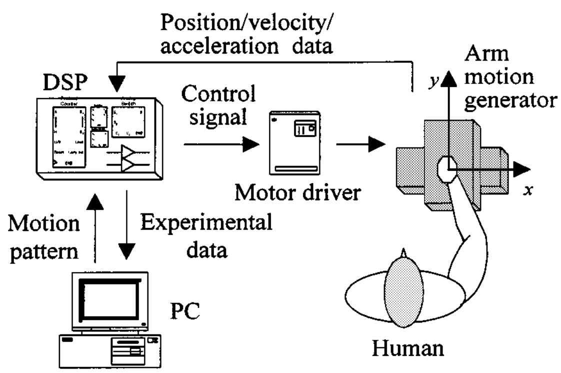

Fig. 2. Arm motion generator system.

the movement of the lever, and then transforms them into information on position, velocity, and acceleration. In addition, it computes control signals required to implement the desired mechanical impedance.

When a subject applies force to the lever of the AMG, he exerts the same amount of force on his hand in the opposite direction, as noted in Newton's law of action–reaction. This force is called reaction force. Thus, when the subject generates motion by exerting force on the lever connected to the motor, the operator will experience a reaction force as follows:

$$F_{\text{total}} = F_{\text{mass}} + F_{\text{damping}} + F_{\text{stiffness}} = M \cdot a + C \cdot v + K \cdot x \quad (1)$$

where F_{mass}, F_{damping}, and $F_{\text{stiffness}}$ are the reaction forces generated by the mass, damping, and stiffness characteristics of the AMG, respectively, and F_{total} is the total force. Impedance in a mechanical system is defined as a measure of motion response to a force exerted on the system, and consists of mass, damping, and stiffness. It is well known that the reaction force due to mass M is proportional to acceleration a, damping C to velocity v, and stiffness K to position x. The reaction due to inertia becomes distinct only when the acceleration is relatively large, but human arms hardly experience such large accelerations because of their limited motion range; however, the acceleration is very important to the body motion subject to rapid velocity changes like being in a rollercoaster. Therefore, only stiffness and damping characteristics are considered in this research. In what follows, therefore, the word "impedance" implies either stiffness or damping.

Equation (1) is an underlying principle that enables the kinesthetic sense to be divided into one generated by stiffness proportional to position and the other by damping proportional to velocity. As mentioned above, stiffness or damping values can be arbitrarily changed in real-time in the arm motion generator by controlling the motor generated forces. Then the kinesthetic sense experienced by the subject can be evaluated whenever the arm motions with different damping or stiffness values are introduced.

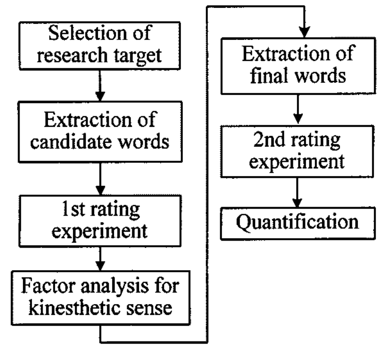

Fig. 3. Flow chart for quantification experiment.

III. Experimental Procedure for Quantification

The experiments for quantification were carried out on 30 subjects who were 20- to 30- yr old college and graduate students according to the procedure shown in Fig. 3.

A. Selection of a Research Target

Since this study focuses on the kinesthetic sense caused by arm movements, the research target is selected as the arm kinesthetic sense. As mentioned in the last section, this arm kinesthetic sense can be divided into stiffness-related and damping-related senses.

B. Extraction of Candidate Words

As many words as possible considered to represent arm kinesthetic sense are collected. These words are candidates for appropriate ones related to the arm kinesthetic sense. They are acquired from dictionaries, various catalogs, and everyday language. It is important that the words containing a similar meaning should be avoided to prevent the subjects from being confused during the experiment. Table I lists the ten candidate words used in this study.

C. Composition of the Semantic Differential Units

The semantic differential (SD) method proposed by Osgood, *et al.* [12] is a method that attempts to get at the underlying meaning which a given concept has. This is usually used for psychological measurement when performing an experiment related to vocabulary. Subjects are asked to rate a given impedance by locating it between two polar adjectives. The space between the adjectives is divided into seven units, indicating closeness of meaning to each of the adjectives [13]. Here the SD approach is implemented using a pair of adjectives, one of which is in the negative, as follows:

strong □□□□□□□ not strong.

The satisfaction level (SL) is defined as the degree of satisfaction that a subject expresses through the SD approach when he is given a certain word for arm kinesthetic sense. It is normalized to have the range between 0 and 1, i.e., $0 \leq \text{SL} \leq 1$). For example, consider the case in which the AMG implements the stiffness of 600 N/m and the word "strong" is presented to the subject. He manipulates the AMG by moving the lever in the way he desires, senses the given stiffness, and then rates his own satisfaction level on the seven units. As the subject feels "stronger" for the given stiffness value, he will select the unit closer to the word "strong," which means a higher satisfaction level.

D. First Rating Experiments

The first rating experiment investigates the subjects' satisfaction levels for the candidate words selected for a wide variety of stiffness or damping values. The genders and ages of subjects are also determined to obtain information on the subjects. Based on the experimental investigation with the AMG, it can be shown that, in general, subjects cannot notice the changes in stiffness and damping less than values of approximately 150 N/m and 40 Ns/m, respectively. Therefore, the intervals of stiffness and damping smaller than these values may cause subjects to be confused in their judgement of kinesthetic sense. In this study, therefore, the interval for stiffness values presented to the subject was set to 200 N/m in the range of 0 to 1000 N/m, while the interval for damping set to 60 Ns/m in the range of 0 to 300 Ns/m.

When the effects of changes in stiffness on human response are investigated, the damping value of the AMG is set to a low value so that the damping characteristics do not affect the psychophysical response to stiffness changes. The same argument applies to the case of damping. In addition, in order to eliminate the effects of the order in which the impedance is presented to the subject, it is presented randomly in magnitude (not in the increasing or decreasing order in impedance values). No load state was inserted between each presentation time so that fatigue accumulation of subjects may be avoided and the kinesthetic sense at no load state may be maintained. Duration of each presentation was determined by the subject, since he was allowed to manipulate the lever as long as he wants, but the average time was about 10–15 s.

E. Extraction of Final Words

Some words among the candidate words for the arm kinesthetic sense listed in Table I are selected by factor analysis based on the results of the first rating experiments. The methods and results of factor analysis are explained in detail in Section IV. By the introduction of factor analysis, the words in Table I are divided into two groups that are adequate for quantification based on either stiffness or damping, respectively. Among these, the final words that are able to represent the entire range of stiffness or damping are selected.

F. Second Rating Experiments

In the same way as in the first rating experiment, subject's satisfaction levels for the final words when a wide variety of impedance values are presented are recorded on the rating paper. The results of the second rating experiments are adopted as the experimental data for this study and quantified by the following procedure.

G. Quantification

Quantification is an operation that transforms data from the second rating experiment to engineering data that are objective, universal, and reproducible, and which can consider the individual's response. The methodology of quantification of kinesthetic sense related to impedance will be dealt with in detail in Section V.

IV. Factor Analysis

A. Methodology

There are many words that can represent the kinesthetic sense related to arm movements, but some statistical analysis methods are needed in order to extract the words for kinesthetic sense adequate both for quantification from the engineering point of view and for reproduction by the AMG. For this purpose, the so-called factor analysis is used,

TABLE I
Candidate Words for Kinesthetic Sense

W1	light	W6	heavy
W2	comfortable	W7	hard
W3	stiff	W8	soft
W4	severe	W9	rough
W5	oppressive	W10	strong

which is one of the multivariable analysis techniques used to simply find a relationship among variables without distinction of dependent and independent variables. In the factor analysis, given variables are represented as the first-order combination of virtual common factors and the change on the whole is explained only by the selected m factors. At this time, the original variables are divided into the m sets based on the magnitudes of coefficients which correspond to each factor, and the meanings of the m common factors are analyzed according to the characteristics of elements in each set. Thus the factor analysis can be understood as a method of variable reduction.

In this study, under the assumption that the change in kinesthetic sense is entirely due to the change in impedance, the subject's satisfaction levels corresponding to given impedances and given candidate words listed in Table I are investigated in the first rating experiment. Since the physical parameters suitable for quantification of each word is different, the candidate words are divided by factor analysis into two groups: one group takes stiffness as a suitable factor for quantification and the other takes damping.

For example, Fig. 4 illustrates the results of the factor analysis based on the satisfaction levels on each of the words listed in Table I with stiffness set to 1000 N/m. The factor analysis has been performed on the condition that the number of factors is two. First, the factor loading is defined as the correlation between the words and the factor, with 0 for no correlation and 1 for maximum correlation. The words whose absolute value of the factor loading is above 0.6 are selected so as to heighten the reliability about the results of the factor analysis. In Fig. 4, variances of factor 1 and 2 are 2.98 and 2.74, respectively, and thus factor 1 is more important than factor 2. That is, the words W3 and W10 assigned to a set that takes the more important factor 1 as a common factor are adequate for quantification with stiffness as a physical parameter.

The factor analysis of damping is also performed in the same procedure as in stiffness, though the analysis results are not shown here. The words for factor 1 are more suitable for quantification of damping than those for factor 2. Hence, the kinesthetic words W2, W6, and W7 assigned by factor 1 are more adequate for quantification for damping than those by factor 2. The kinesthetic words adequate for quantification with damping as a physical parameter are extracted in the way of the procedure performed for stiffness.

B. Results of Factor Analysis

Using the method of factor analysis described previously, the candidate words are arranged in the descending order of the factor loading in Tables II and III for stiffness and damping, respectively. In the case of stiffness, from Table II, the word W10 (strong) seems to be adequate for the entire range of stiffness. Some words such as W3, W6, and W7 are only adequate for the partial range of stiffness.

In the case of damping, from Table III, the word W5 (oppressive) is adequate for the entire range of damping. As in the case of stiffness, some words such as W3, W6, W7, and W9 are adequate for the partial range of damping. Figs. 5 and 6 depict the satisfaction level versus stiffness and damping ranges, respectively. They show the words whose

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The SAS System

Orthogonal Transformation Matrix
              1          2

   1     0.75881   -0.65132
   2     0.65132    0.75881

      Rotated Factor Pattern

             FACTOR1    FACTOR2

Q3          0.97112   -0.05792
Q10         0.87269   -0.12795
Q9          0.56345   -0.00905
Q5          0.56107   -0.21390
Q2         -0.13635    0.93767
Q8          0.41167    0.57036
Q1         -0.47859    0.54441
Q4          0.26416   -0.34597
Q7          0.39951   -0.64915
Q6         -0.01010   -0.79617

Variance explained by each factor

        FACTOR1    FACTOR2
       2.983551   2.741472
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Fig. 4. Results of factor analysis ($k = 1000$ N/m).

TABLE II
RESULTS OF FACTOR ANALYSIS FOR STIFFNESS

Stiffness (N/m)	Factor 1	Factor 2
200	W2, W1, W10	W3,W6,W5,W8
400	W4,W9,W7,W10,W8	W5,W6
600	W7,W10,W5,W6	W8,W1,W3
800	W10,W6,W3	W1,W8,W4
1000	W3,W10	W2,W7,W6

TABLE III
RESULTS OF FACTOR ANALYSIS FOR DAMPING

Damping (Ns/m)	Factor 1	Factor 2
60	W5,W3,W1,W2	W9,W6,W10
120	W3,W10,W9,W5	W4,W2,W1,W6
180	W3, W7, W5, W9, W10, W1	W4,W2,W6,W5
240	W7,W6,W9,W5,W8	W4,W3,W1,W10
300	W10,W6,W5,W2	W1,W4,W7

dominant parameters are stiffness and damping according to Tables II and III. In summary, the final words W10 (strong) and W5 (oppressive) are chosen as representative of stiffness and damping, respectively.

V. Quantification Procedure

The quantification method for arm kinesthetic sense proposed in this study is divided into two steps as shown in Fig. 7. The first step is the quantification by which the satisfaction levels are inferred over the entire range of impedance, i.e., stiffness or damping, based on the data acquired from the second rating experiment. By this first quantification, an average kinesthetic sense for each impedance level can be obtained by analyzing the data of all the subjects. For example, for the stiffness of 600 N/m and the word "strong," the average satisfaction level for 30 subjects is about 0.8 (see Table IV). However, the individual kinestheticsense cannot be properly reflected in this quantification. As

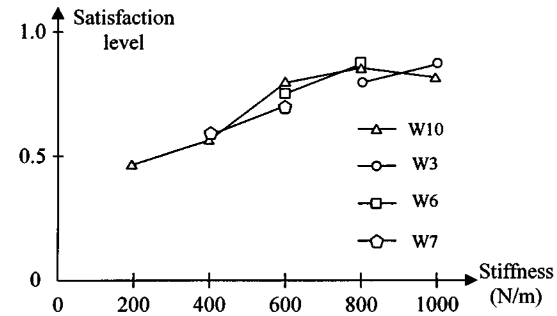

Fig. 5. Satisfaction level versus stiffness for various words.

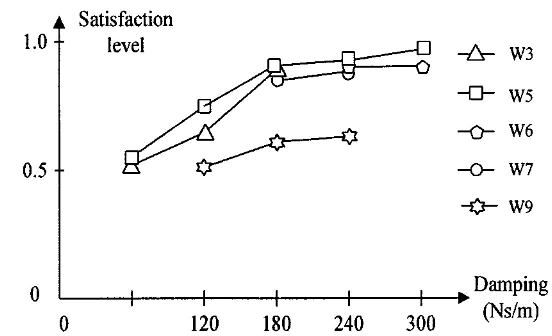

Fig. 6. Satisfaction level versus damping for various words.

the second step, therefore, individual differences of each subject are analyzed in the second quantification by properly reflecting the individual differences in the average kinesthetic sense obtained in the first quantification.

A. First Quantification

As a result of factor analysis, the words "strong" and "oppressive" were selected as the final words for kinesthetic sense related to stiffness and damping, respectively. Then the satisfaction level of each subject was investigated for these two words by the second rating experiment. In Fig. 7, $y_i(x_j)$, where $i = 1, \cdots, n$ (the total number of subjects), $j = 1, \cdots, m$ (the total number of presented impedances), means the satisfaction level of subject i when the jth impedance is presented through the AMG. Tables IV and V represent the average satisfaction levels computed from the data $y_i(x_j)$ of all subjects in each range of impedance.

The satisfaction levels in the tables are just responses for only five stiffness or damping values, and interpolation is needed to obtain the satisfaction levels for the arbitrary impedance values that are not covered by these discrete values. For this purpose, the following sigmoid function is selected

$$\hat{y}(x) = y_o + \frac{a}{1 + e^{-(x - x_o)/b}} \tag{2}$$

where $\hat{y}(x)$ denotes the mean satisfaction level for the arbitrary impedance value x. The parameters a, b, x_o, and y_o in (2) are calculated from the mean satisfaction levels in Tables IV and V, and the numerical values are listed in Table VI. It is noted that the sigmoid function is adopted because the general shape of the curve of satisfaction level versus impedance is described well by the S-shaped curve and the sigmoid function can provide this shape naturally.

The mean satisfaction levels obtained by the above procedure are a standard for kinesthetic sense as data with objectivity, universality, and reproducibility. But the largest problem in quantifying human responses is that there exists no absolute standard for it. In other words,

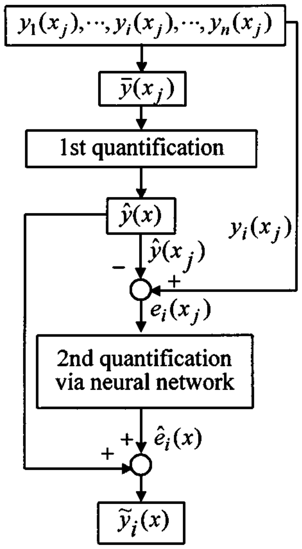

Fig. 7. Quantification of arm kinesthetic sense.

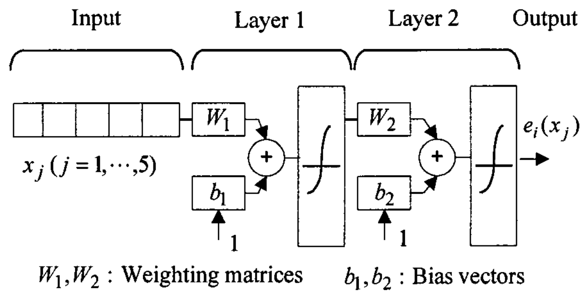

Fig. 8. Configuration of neural network.

TABLE IV
MEAN SATISFACTION LEVELS ASSOCIATED WITH THE WORD "STRONG"

Stiffness no. (*j*)	1	2	3	4	5
Stiffness (N/m)	200	400	600	800	1000
Satisfaction level	0.47	0.57	0.80	0.85	0.90

TABLE V
MEAN SATISFACTION LEVELS ASSOCIATED WITH THE WORD "OPPRESSIVE"

Damping no. (*j*)	1	2	3	4	5
Damping (Ns/m)	60	120	180	240	300
Satisfaction level	0.52	0.66	0.90	0.95	0.95

TABLE VI
PARAMETERS OF QUANTIFICATION FUNCTION OF MEAN KINESTHETIC SENSE

	a	b	x_o	y_o
Stiffness	19.8	140.0	-1038.0	-18.8
Damping	14.8	87.6	-230.7	-13.8

TABLE VII
DATA OF SUBJECTS ASSOCIATED WITH STIFFNESS

Stiffness (N/m)		200	400	600	800	1000
Satisfaction Level	Subject 1	0.28	0.42	0.85	0.85	1.00
	Subject 2	0.71	0.57	0.85	0.85	1.00
	Subject 3	0.42	0.71	0.71	0.85	0.71

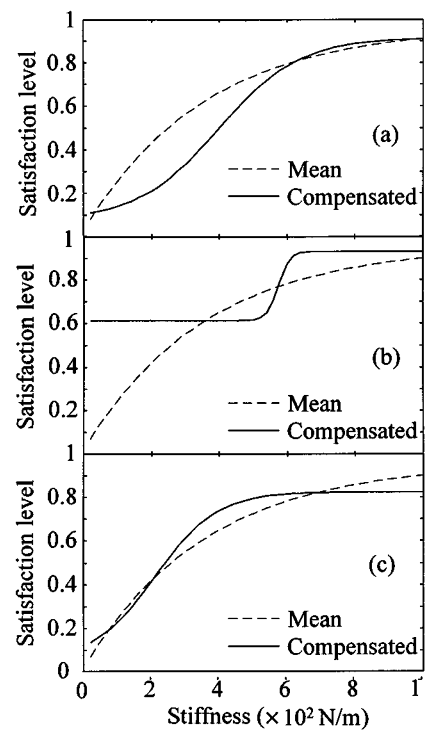

Fig. 9. Quantification with compensation regarding stiffness: (a) subject 1, (b) subject 2, and (c) subject 3.

each individual tends to show different psychophysical responses for the same impedance values. For kinesthetic sense data to have meaning from the engineering point of view, when impedance is presented with each satisfaction level for each word through the AMG, subjects should experience corresponding kinesthetic senses. It follows from this discussion that compensation for individual differences of each subject is required.

B. Second Quantification

The second quantification is mainly performed through a neural network scheme. The neural network well represents a nonlinear relationship between the input and output, and has robustness properties for arbitrary inputs as well as direct inputs within the input bounds. Furthermore, fast operation is possible by obtaining the relationship between the input and output by only matrix operations of inputs, weighting factors, and biases [14]. Fig. 8 illustrates the diagram of the neural network used in this study. In the learning process of a neural network, the improved back propagation algorithm that includes momentum and renews the learning rate at each learning time was adopted.

As shown in Fig. 8, five impedance values are defined as input x_j and the individual difference is defined as output $e_i(x_j)$, respectively. Next, weighting matrices (W_1, W_2) and bias vectors (b_1, b_2) were calculated as a result of learning the relationship between the inputs and outputs. Subsequently, the individual difference $\hat{e}_i(x)$ of subject i on any impedance value x within the entire range can be calculated. That is, the individual differences not included in the experiments can be obtained by interpolation using the neural network. The individual difference $\hat{e}_i(x)$ for any arbitrary impedance value x is then added to the mean satisfaction level $\hat{y}(x)$ to compensate for individual differences.

TABLE VIII
DATA OF SUBJECTS ASSOCIATED WITH DAMPING

Damping (Ns/m)		60	120	180	240	300
Satisfaction level	Subject 1	0.57	0.71	0.85	1.00	1.00
	Subject 2	0.42	1.00	0.85	0.85	0.85
	Subject 3	0.57	0.28	1.00	1.00	1.00

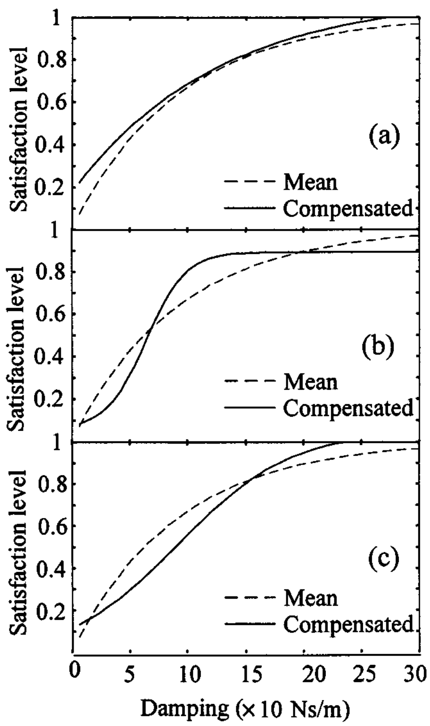

Fig. 10. Quantification with compensation regarding damping: (a) subject 1, (b) subject 2, and (c) subject 3.

Comparing each subject's data with the mean satisfaction level, a difference of individual strength and inclination of kinesthetic sense can be inferred. However, the individual difference depends mostly on the environment or condition of a subject during the experiment. In addition, an irregular variation of the satisfaction level might exist at each range of impedance. If these data are presented to the subjects without filtering out uncertainty, it may work as an obstacle to maintenance of human responses.

1) Case of Stiffness: A random selection of 3 subjects was made out of 30 subjects participating in the experiment, and they were called Subject 1, 2, and 3, respectively. Table VII lists the results of the second rating experiments performed by these subjects for the word "strong" and Fig. 9 shows the kinesthetic sense $\tilde{y}_i(x)$ which is compensated for individual difference based on Table VII. In the case of Subjects 1 and 3, individual satisfaction levels show some variation over the range of stiffness, with respect to the mean satisfaction level. Subject 3 shows little change in response above the stiffness of 500 N/m, while Subject 2 shows sudden change in the response in the range of 500~630 N/m but is nearly insensitive to changes in stiffness for other ranges. As a result, the quantification function that compensates for individual difference is on the whole similar to the inclination of data in Table VII, and smoothes out the sudden, abnormal changes in the satisfaction levels.

2) Case of Damping: As in the case of stiffness, 3 subjects were randomly chosen, and the second rating experiments were performed by these subjects for the word "oppressive." Table VIII lists the results and Fig. 10 shows the kinesthetic sense $\tilde{y}_i(x)$ which is compensated for individual difference based on Table VIII. Subject 1 shows a slightly higher satisfaction level on the whole compared with the mean value. That is, Subject 1 tends to feel oppressive for the smaller damping value than the one needed to generate the mean value. Subject 2 seems to be insensitive to changes in damping above the damping of 130 Ns/m. Subject 3 shows some variations in the satisfaction level, and is completely satisfied above the damping of 250 Ns/m.

VI. CONCLUSION

In this study, an algorithm is presented that quantifies human responses to changes in stiffness or damping values generated by an AMG. The words "strong" and "oppressive" were selected as adequate words for quantification for stiffness or damping, respectively, by means of the semantic differential method and factor analysis. Through the proposed experimental procedure, the average kinesthetic sense is computed based on the data of many subjects. In order to reflect the individual differences of each subject in the kinesthetic sense, compensation for individual differences is performed through the neural network technique.

Using the algorithm presented in this research, the human responses to arm movements described qualitatively can be converted into engineering data ensuring objectivity, reproducibility, and universality. The quantified data can be used to develop user-friendly products related to arm motion and induce the inclination of individual kinesthetic sense. Further research will focus on the expansion of this algorithm to more sophisticated human motion.

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