MEASUREMENT AND VALUATION OF TOUCH SENSATION (TACTILE PERCEPTION OF FOREFINGER COMPARED WITH PVDF SENSOR OUTPUT)

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ABSTRACT

This paper is a study on the valuation and mathematical formulation of human touch sensation. First, the specific feelings of touch are collected on five natural and chemical fabrics through the SD (Semantic Differential) method questionnaire handed onto twenty eight subjects. The feelings are valued on every fabric by obtaining the weigthed mean overall rating of touch on every fabric by a linear function of the valuations on specific feelings of touch. Next, a soft tactile sensor made of a PVDF (Polyvinylidene Fluoride) film with an electrode patch and rubber layers is assembled and slid over the same sample fabrics to collect the surface tactile information of the fabric. The features on the collected data are then extracted by calculating the temporal average of absolute outpput signal and the intensity of power in the mid-frequency range. Comparison of the results show that the PVDF sensor well describes the tactile perception of forefingers.

Key words: Sensor, Measurement, Tactile Perception, PVDF Sensore, SD method, Multiple Regression Analysis.

1. INTRODUCTION

Of all our senses,the sense of touch is the most intimately connected to our feeling. In our daily life, various kinds of things are touched by the fingers and their physical as well as geometrical features are extracted and evaluated. Thus, the sense of touch is indispensable to our human life as the sense of sight. In our tactile function of fingers, the digital pulp is pressed against the object and then the stroke or rubbing action is started over the surface of the object in order to feel the texture. It seems that most of the force sensors developed so far have been functional to the measurement of the force magnitude [1], while only a few sensors are available for the rating of texture on the object materials [2-3]. It is well known that the output of the polyvinylidene fluoride (PVDF) film measured in the form of current is proportional to the rate of the strain induced in the film. Experimental results show that the output signal from the polymer film takes the form of a brief potential wave at the onset of the pressure pulse and a similar brief wave at the termination, further there is no response during the stationary plateau of the applied pressure. The time varaition is quite similar to the response of the Pacinian corpuscle which is a sensory recepter in the dermis particularly functional to the touch-vibration of 25—300Hz[4]. Recently, the present authors have assembled a tactile sensor made of PVDF films ınd soft rubber layers and measured the output current signals from the polymer ïlms by pressing the sensor against various kinds of soft materials. It was verified hat the piezopolymer sensor extracts the features on the stiffness of materials and ıas the potential to be used as a soft palpation sensor [5].

Гhis paper is a study on the measurement and valuation of touch sensation. The :actile perception of forefinger is compared wth the output of piezopolymer sensor. First, the objetive specific feelings of touch are collected on five fabrics through the questionnaires based onteh semantic differential method. The subjective overall rating of touch is then represented as a linear function of the valuations on specific feelings with the aid of the multiple regression analysis. Next, a soft tactile sensor made of a PVDF film with an electrode patch and rubber layers is fabricated and slid over the same sample fabrics to collect the surface tactile information on the fabrics. The features on each fabric are extracted through the processing of collected data. Comparison fo the results show that the active sensing the PVDF sensor can be used as a substitute for the tactile function of human forefinger.

2. MEASUREMENT OF HUMAN TACTILE SENSATIONS

First, the human touch sensation was examined by using the forfinger and five natural and chemical fabrics. Twenty eight subjects (12 female and 16 male) were asked to touch and feel small pieces of cloths of wool, figured satin, velvet, crepe nad corduroy, all of which were laid inside a blind box and hidden from the subject's view so that they evaluate the fabrics only by the sense of touch. The direction of rubbling over the fabrics was ruled from left to right since the feelings of touch are dependent on the direction of the texture. The subjects were asked to report their feelings of touch and the overall rating of touch through the questionnaire based on the SD (Semantic Differential) method.

2.1 COLLECTED INFORMATION ON FEELINGS OF TOUCH

Figure 1 is the questionnaire handed onto the subjects. It covers a number of aspects of human tactile perception. Each subject was requested to complete the form on every fabric. Seven specific feelings on the quality of texture, which are listed up and down, are subdivided into a five-step scale from left to right with the rate of -1 through 1 allotted to each step. The specific feelings on each fabric were valued by calculating the weighted mean on the 28 data from the subjects. The results of evaluation are presented in Table 1. In the same manner, the overall rating of touch was evaluated by using a five-step scale ranging from "very uncomfortable" to "very comfortable", each allotted with the rate of -1 to 1. The individual data on the overall rating of touch and the average are presented in Tables 2 and 3, respectively.

To find the correlation of the specific feelings, the correlation coeffecient defined by

$$r = \frac{\sum_{i=1}^{7} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{7} (x_i - \bar{x})^2 \sum_{i=1}^{7} (y_i - \bar{y})^2}} \qquad (1)$$

Table 1 Valuations on specific feelings

	A(Wool)	B(Figured Satin)	C(Velvet)	D(Crepe)	E(Corduroy)
Roughness	0.5417	-0.9375	-0.1250	0.7917	0.1042
Softness	0.1875	-0.2292	0.8125	-0.5417	0.4375
Moistness	0.0417	0.3542	0.500	-0.6667	0.1458
Coolness	-0.2500	0.4375	-0.8125	0.5208	-0.5833
Elasticity	0.0833	-0.4130	0.6667	-0.5208	0.5000
Fineness	-0.417	0.7708	0.1250	-0.3542	-0.2500
Short-Trimmed	0.1875	0.9375	-0.875	0.8542	-0.4375

Table 2 Individual data on overall rating of touch

	A(Wool)	B(Figured Satin)	C(Velvet)	D(Crepe)	E(Corduroy)
Female ♯ 1	-0.5	-1	0.5	-0.5	0
2	-1	0	1	-0.5	-0.5
3	-0.5	0	0	-0.5	0.5
4	0	-1	1	-0.5	0.5
5	-0.5	1	0	-1	0
6	0	-0.5	0	-1	0
7	-0.5	0.5	1	-1	0
8	-0.5	0.5	1	1	1
9	-0.5	-0.5	0.5	1	0.5
10	-0.5	1	1	-0.5	0
11	-1	0	1	-0.5	0.5
12	-0.5	0	0.5	-0.5	0
Male ♯ 1	0.5	-1	1	0.5	0.5
2	0	-0.5	0.5	-0.5	0.5
3	-0.5	-0.5	0.5	-1	0
4	0	-0.5	1	-1	0.5
5	0	0	1	-1	0.5
6	-0.5	0.5	1	-0.5	0
7	0.5	0	0	-0.5	0
8	0	-0.5	1	-0.5	0
9	-0.5	0	0.5	0	0.5
10	-0.5	0.5	1	-0.5	0.5
11	-1	0.5	0	-0.5	-0.5
12	0	0.5	1	-0.5	0
13	-0.5	1	0	0	-0.5
14	-0.5	0	0	-0.5	0
15	-0.5	-0.5	-0.5	-0.5	-0.5
16	0	0.5	1	0	1

Table 3 Overall rating of touch

	A(Wool)	B(Figured Satin)	C(Velvet)	D(Crepe)	E(Corduroy)
Valuation	-0.3393	0.0000	0.5893	-0.4107	0.1786

Table 4 Correlation coefficients of specific feelings

	Roughness	Softness	Moistness	Coolness	Elasticity	Fineness	Short Trimmed
Roughness	1.0000	-0.1523	-0.7542	-0.0255	-0.0246	-0.9559	-0.0411
Softness		1.0000	0.7332	-0.9794	0.9799	-0.0514	-0.9638
Moistness			1.0000	-0.5949	0.6135	0.5936	-0.5459
Coolness				1.0000	-0.9959	0.2413	0.9842
Elasticity					1.0000	-0.1940	-0.9887
Fineness						1.0000	0.2300
Short Trimmed							1.0000

Table 5 Correlation coefficients of overall rating of touch

	A(Wool)	B(Figured Satin)	C(Velvet)	D(Crepe)	E(Corduroy)
A(Wool)	1.000	-0.3638	-0.1214	0.0178	0.3358
B(Figured Satin)		1.000	0.0000	0.0296	-0.1512
C(Velvet)			1.000	0.1153	0.4846
D(Crepe)				1.000	0.3912
E(Corduroy)					1.000

are introduced and calculated. In the above equation, xi and yi, i = 1, ..., 5, are the valuations on feelings x and y of fabric i, and x and y are the mean of xi and yi. The correlation coefficient calculated on the valuations of Table 1 are presented in Table 4. It is noted that a positive correlation is observed between "elaticity", and softness" and "short-trimmed and coolness", further a negative correlation between "coolness and softness", "elasticity and coolness", "short-trimmed and softness", "short-trimmed and elasticity" and fineness and roughness". The positive corelation means that the two feelings of touch are very much alike while the negative correlation vice versa.

It is noted from the comparison of above classification that the feelings of touch are assorted into three groups of,

a: Thick-piled, Warmth, Softness, Elasticity,
b: Roughness, Coarseness,
c: Moistness.

One find here which specific feelings of touch contribute mostly to the overall rating of touch. The correlation coefficients on the overall rating of touch of Table 2 are presented in Table 5. A clear positive correlation is observed between the ratings of the velvet and the corduroy, while a negative one on the ratings of the wool and the figured satin. For the specific feelings of touch of Table 1, the feelings with similar valuations corresponds to the positive correlation, while the feelings having separate valuations to the negative correlation. The specific feelings of touch that bring about similar valuations on the velvet and the corduroy while separate valuations on the wool and the figured satin are "roughness" and finness". Thus, it is said that the overall rating of touch is determined mostly dependent on "roughness" and "finness"

2.2 MULTIPLE REGRESSION ANALYSIS

The overall rating of touch is determined from the total information on the specific feelings of touch as "roughness", "softness" and the others. To formulate the overall rating of touch as a linear function of the specific feelings, one here introduce the multiple regression analysis[6]. It is a method of analysis to deal with the causal relation. The objective variable y is described by a linear function of the factor variables
x_p, p=1,2, ... as
$y = b_0 + b_1x_2 + \ldots + b_p x_p$, (2)

where b_0 through b_p are partial regression coeficients. The error of the regression estimator to the sample value is called the estimated error . The partial regression coefficients b_p are determined so that the sum square of defined by

$$S = \sum_{\lambda=1}^{N} \epsilon_\lambda^2 = \sum_{\lambda=1}^{N} (y_\lambda - \hat{y}_\lambda)^2$$
$$= \sum_{\lambda=1}^{N} [y_\lambda - (b_0 + b_1 x_{1\lambda} + b_2 x_{2\lambda} + \cdots + b_p x_{p\lambda})]^2. \quad (3)$$

takes on a minimum value. With the use of equation (2), the regression estimator are given by

$$\left.\begin{aligned} \hat{y}_1 &= b_0 + b_1 x_{11} + b_2 x_{21} + \cdots + b_p x_{p1}, \\ \hat{y}_2 &= b_0 + b_1 x_{12} + b_2 x_{22} + \cdots + b_p x_{p2}, \\ &\vdots \\ \hat{y}_N &= b_0 + b_1 x_{1N} + b_2 x_{2N} + \cdots + b_p x_{pN}, \end{aligned}\right\} \quad (4)$$

for N set of factor variables $x_{1\lambda}, x_{2\lambda}, \cdots, x_{p\lambda}, \lambda = 1, 2, \cdots, N$.

In general, the derived multiple regression function is evaluated by calculating the multiple correlation coefficient R. It is a correlation coefficient of the regression estimator to the sample value given by

$$R = \frac{\sum_{\lambda=1}^{N} (y_\lambda - \bar{y})(\hat{y}_\lambda - \bar{\hat{y}})}{\sqrt{\sum_{\lambda=1}^{N} (y_\lambda - \bar{y})^2 \sum_{\lambda=1}^{N} (\hat{y}_\lambda - \bar{\hat{y}})^2}}, \quad (5)$$

where and are the mean of and are allotted to the wool, figured satin, ... and corduroy, respectively.

The multiple regression analysis is done by assuming the evaluations on specific feelings as the factor variavles and the overall rating of touch as the sample value since the feelings of touch were classified into three groups of a, b and c, the number of objective variables was set at p = 3.

Three specific feelings were picked up from the 3 groups of a, b and c as factor variables , and the multiple regression analysis was done on the selected set of variables. The determined partial regression coefficients b_p and the multiple correlation coefficient R are given in Table 6. It is noted that the multiple correlation coefficient is very close to unity for every set of the factor variables. Particularly, the coefficient R is nearly equal to 1 for the set of "short-trimmed", "fineness" and "moistness". The regression function in this case is,

$$\hat{y} = 0.1441 - 0.6546x_1 + 0.8088x_2 - 0.4401x_3. \quad (6)$$

The estimator on the overall rating of touch of equation (6), the sample value of Table 3 and the estimated error are listed in Table 7. In every case the estimated error is sufficinently small, and it is said that the regression function obtianed in the analysis well describes the human perception on the feeling of touch.

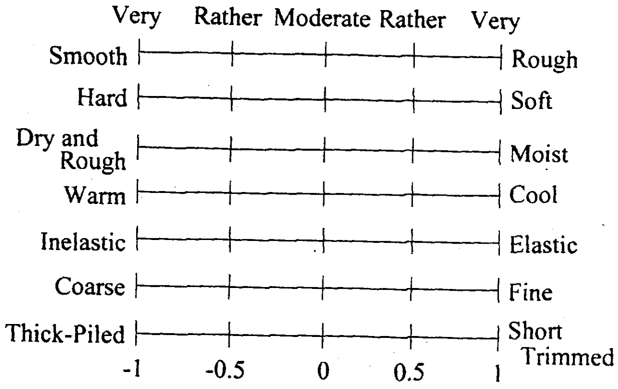

Fig 1 Questionnaire based on semantic differential method.

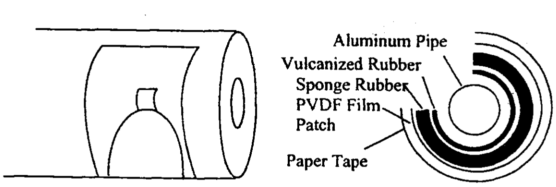

Fig 2 Geometry of PVDF piezopolymer sensor.

3. MEASUREMENT BY PVDF SENSOR

A cylindrical soft tactile sensor made of PVDF (Polyvinylidene Fluoride) film and rubber layers was fabricated and slid over the sample fabrics to collect the information on the quality of the surface. The sensor is an assembly of layered media as presented in Fig.2. The base of the sensor is an aluminum cylindrical shell of outer diameter 9mm, on which a thin vulcanized rubber (1mm thickness), a core sponge rubber of thickness 3mm, a PVDF film with an electrode patch of diameter 12mm and a protective paper tape were stacked in sequence. The paper tape has a coarse surface and is furnished with the function of the fingerprint. Figure 3 illustrates the experimental setup for measuring the texture of the fabrics. The sensor is pinched between the thumb and the index finger and slid over the fabric with the contact force and speed. The output signal fromthe piezopolymer film is measured for 100msec and sent to a digital oscilloscope (HITACHI VC-7542) every sampling time of 0.2msec, further forwarded to a personal computer (NEC PC - 9821 Nd2) via a GP-IB (ADTEK SYSTEM SCIENCE AXP - GP01) as 500 8-bit signals for data processing. Some typical out-put signals from the sensor are presented in Fig.4. The output of the piezoppolymer film measured in the form of electric current is proportional to the rate of the strain induced in the film, which means that the maximum amplitude is rather superposed by the noises from measuring system. Because of this, the temporal average of the absolute output signal was used as an index to extract the feature of the collected data, i.e.,

$$I = \frac{1}{k}\sum_{k=1}^{K} I_k \tag{7}$$

where

$$I_k = \frac{1}{T}\sum_{n=1}^{N} |V_k(n)|\delta t = \frac{1}{N}\sum_{n=1}^{N} |V_k(n)|,$$
$$T = N\delta t, N = 500, \delta t = 0.2\text{msec}.$$

Here, V_k and I_k are the output and the integrated value on the k-th reading, and I is the average of I_k.

The measurement was done several times on every fabric and the average of I_k was used as the sensor output.

Table 6 Partial regression and multiple correlation coefficients for various sets of factor variables

Factor Variable x_1	Factor Variable x_2	Factor Variable x_3	b_0	b_1	b_2	b_3	R
Softness	Roughness	Moistness	0.0049	1.4424	-0.9618	-1.6198	0.9787
Softness	Fineness	Moistenss	-0.0685	1.4692	1.1066	-1.2817	0.9948
Coolness	Roughness	Moistness	0.0079	-0.9615	-0.8361	-0.9840	0.9396
Coolness	Fineness	Moistness	-0.0517	-1.3066	1.3647	-1.2025	0.9997
Elasticity	Roughness	Moistness	0.0412	0.9116	-0.6248	-0.6459	0.9410
Elasticity	Fineness	Moistness	0.0155	1.2209	1.0403	-0.8420	0.9944
Short-Trimmed	Roughness	Moistness	0.1824	-0.6189	-0.6608	-0.6228	0.9814
Short-Trimmed	Fineness	Moistness	0.1441	-0.5646	0.8808	-0.4401	0.9998

Table 7 Results of multiple regression analysis * Table 3

	Regression Estimator $\hat{y}_\lambda$	Sample Value y^*_λ	Error ϵ_λ
A (Wool)	-0.3340	-0.3393	-0.0053
B (Figured Satin)	-0.0021	0.0000	0.0021
C (Velvet)	0.5979	0.5893	-0.0086
D (Crepe)	-0.4081	-0.4107	-0.0026
E (Corduroy)	0.1641	0.1786	0.0145

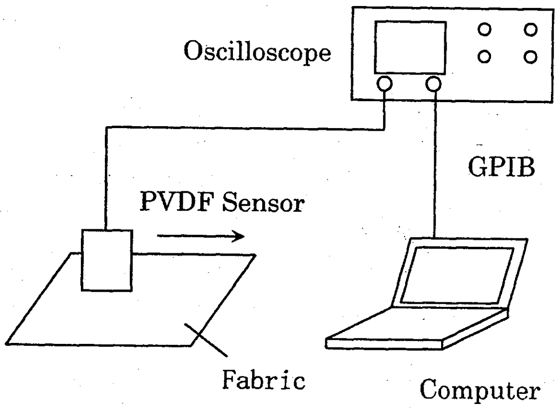

Fig 3 Experimental setup.

Table 8 Output of PVDF sensor

Fabrics	Sensor Output I
A (Wool)	0.000246
B (Figured Satin)	0.000129
C (Velvet)	0.000150
D (Crepe)	0.000282
E (Corduroy)	0.000161

Table 9 Correlation of sensor output with specific feelings

	Roughness	Fineness
Correlation Coefficient	0.9026	-0.7658

The output of sensor I on the sample fabrics are presented in Table 8. It is seen that the output of the wool and the crepe is greater than the output of other fabrics. Comparison of Table 8 with Table 1 leads to an understanding that the fabrics according to the magnitude of I are in the same order as the fabrics on the feeling "roughness", while it is in the reverse order to that of the fabrics on the feeling "fineness". Those two specific feelings are the ones that have been classified into Group b in section 2.1. The correlation coefficients of the sensor output of Table 8 with the valuations of "roughness" and "fineness" given in Table 1 were obtained and are presented in Table 9. It is clear that the sensor output has strong correlation with the two feelings. The valuations of "roughness" and the sensor output are replotted in Fig.5 with their least-squares regression line.

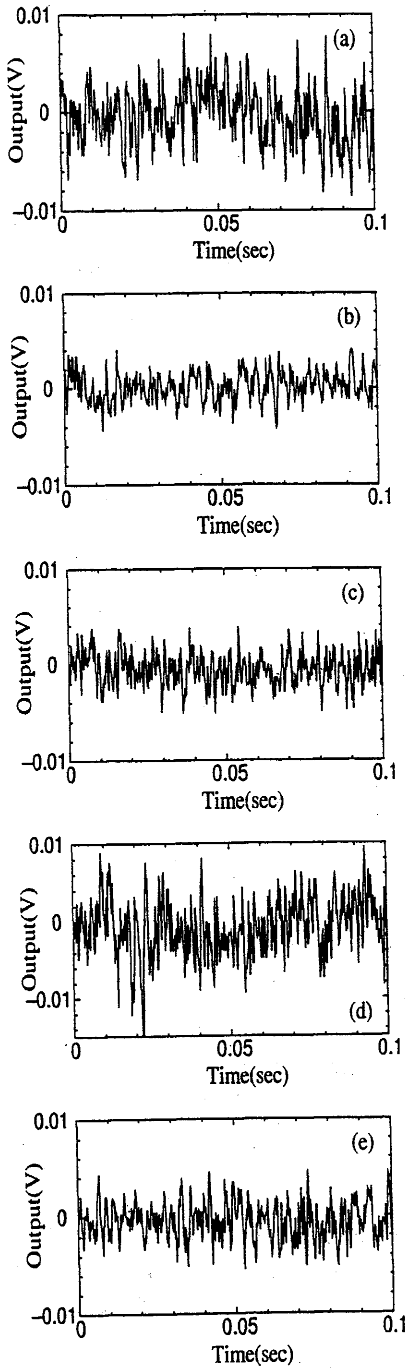

Fig 4 Output of PVDF sensor on (a)wool, (b)figure satin,(c)velvet,(d)crepe and (e)corduroy.

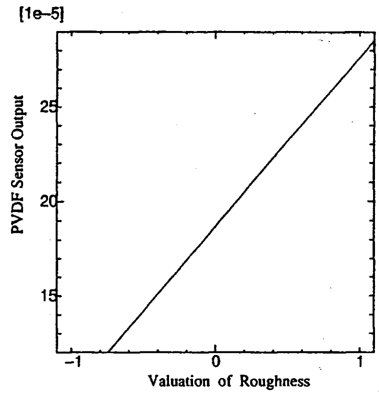

Fig 5 PVDF sensor output versus valuation of roughness given in Table 1.—,Regression line.

The FFT analysis is then introduced to extract the features on the collected data. Figure 6 presents the power spectrum densities on the output of Fig.4. It is seen that the power is mostly distributed in the frequency range lower than 2000Hz. It is well known that the human sensitivity on the vibration is such that he/she can discriminate the vibration of 30Hz with a peak-to-peak amplitude of 20 while feel the movement of p-p amplitude of 2 with 200Hz[7]. Thus, the human tactile perseptions are concerned with the vibratory signals at the mid-frequency. Becuase of this, the following analytical attention is focused on the output signals and the intensity of power in the mid-frequency range.

The ratio of the power in mid-frequency range to the power over mid-high frequency range, whichis refered as mid-frequency power intensity, is given by

$$R_s = \frac{S_a}{S_b}, \tag{8}$$

where

$$S_a = \sum_{n=f_1}^{f_2} P(f), \qquad S_a = \sum_{n=f_1}^{f_3} P(f).$$

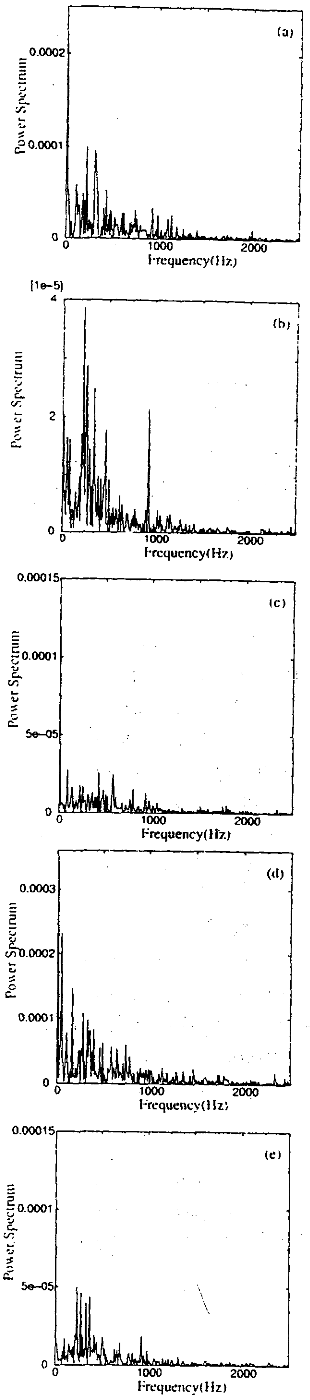

Fig 6 Power spectrum density of sensor output on (a)wool, (b) figured satin, (c)velvet, (d)crepe and (e)corduroy.

Table 10 Mid-frequency power intensity

Fabrics	R_s
A(Wool)	0.5555
B (Figured Satin)	0.6180
C (Velvet)	0.4817
D (Crepe)	0.5724
E (Corduroy)	0.5475

Table 11 Correlation of mid frequency power intensity with valuation on specific feeling of Group a

Softness	Coolness	Elasticity	Short-Trimmed
-0.8226	0.8524	-0.8397	0.9059

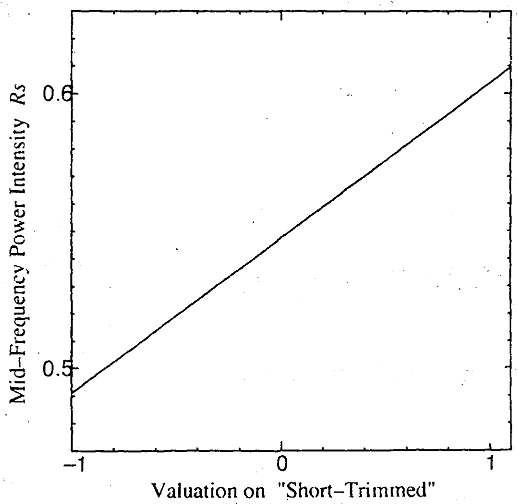

Fig 7 Mid-frequency power intensity versus valuation on "short-trimmed" given in Table 1. ,Regression line.

Here, P(f) denotes the power spectrum density. In the following calculation, the f1, f2 and f3 have been set at 100Hz, 500Hz and 2000Hz, respectively. The obtained results are presented in Table 10. Comparing the intensity Rs with the valuations of Table 1, it is found that the fabrics according to the intensity of Rs are in the same order as the fabrics on the feeling "short-trimmed". With this fact in mind, the specific feelings of Group a, which enrolls the feeling "short-trimmed", was compared with the power intensity of Table 10. The results are presented in Table 11. The correlation of the intensity with the feelings of Group a is selfevident. The valuations of "short-trimmed" in Table 1 and the power intensity of Table 10 are replotted in Fig.7 together with the least-squares regression line.

The results given above lead to a finding that the temporal average of the absolute output signal of PVDF sensor has a clear correlation with the specific feelings of Group b. Further, the intensity of power in the mid-frequency range has another definite correlation with the feelings of touch of Group a.

4. CONCLUSIONS

A theoretical and experimental study has been presented for the measurement and valuation of human touch sensations. The tactile perception of forefinger has been compared with the output of PVDF piezoplymer sensor. The obtained results can be summarized as follows.

1. The tactile peception of forefinger was measured by using the questionnaire based on the semantic differential method, from which the specific feelings of touch and the subjective overall rating of touch were valued numerically. By using the multiple regression analysis, the overall rating of touch was then represented by a linear function of the specific feelings.

2. A soft tactil sensor made of a PVDF piezopolymer film and matrix rubber layers was fabricated and the surface tactile inforamtion on the sample fabrics was collected by sliding the sensor over the fabrics. The temporal average of the absolute output signal and the power intensity in the mid-frequency range were found to have clear correlations with several specific feelings of touch of the forefinger.

3. The tactile sensor assembled here has a function of predicting several specific feelings of touch, which means the overall rating of touch can also predicted by the sensor.

Since the assembled PVDF sensor was found to have a tactile function of fingers, the current and future work include in corporation of sensor into a robotic finger[8] and its application to active sensing for discriminating the fabric by feeling the texture.

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