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A Quantitative Evaluation Method of Handedness Using Haptic Virtual Reality Technology

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1. Introduction

Quantitative evaluation of handedness of people will be useful in various situations. For example, handedness is an important factor in designing tools and devices that are to be handled by people using their hands. It will also be useful for knowing the degree of recovery of a person in rehabilitation stage suffering from injury or disease.

A well-known method for evaluating handedness of a person is LQ (laterality quotient)-method (Oldfield, 1971) which is based on the answers to ten questions such as which hand one uses for writing letters. Matsuda et al. (1986) propose to evaluate handedness based on the results of tests of tapping, peg-board, and picking up beans using discriminant function analysis.

There are many researches trying to find functional differences between dominant and non-dominant hands. Fujiwara et al. (2003) use a digital trace method for studying the difference of upper limb coordination between dominant and non-dominant hands. Wu et al. (1996) examine the difference between the behaviors during the operation of touch panel by the dominant and non-dominant hands. Bagesteiro & Sainburg (2002) investigate interlimb differences in coordination through analysis of inverse dynamics and electromyography recorded during the performance of reaching movements. These studies assume that subjects in their experiments can be divided into two groups: right-handed persons and left-handed persons. One possible direction of future research will be to consider the quantitative degree of handedness of each subject.

Haptic virtual reality is a technology which makes it possible for us to see and touch a virtual environment composed by a computer through a haptic display device. Various researches have been done so far in this field (Burdea, 1996). We have proposed a methodology for displaying the dynamics of virtual objects (Yoshikawa et al., 1995). We have also developed a system for observing human skill by using a virtual task space (Yoshikawa & Yoshimoto, 2000).

A method is proposed in this chapter for evaluating quantitatively the handedness and dexterity of a person from his/her performance of some test tasks in the virtual world that are constructed using haptic virtual reality technology. The merits of virtual test tasks over

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real tasks are that it is easier to provide a large variety of tasks, to change the values of parameters of these tasks, and to obtain detailed position and force data for evaluation.
We prepare three test tasks: accurate positioning task, accurate force control task, and skillful manipulation task. Performance data for these test tasks taken from a group of subjects are analyzed using the factor analysis. Since the obtained factor scores for the right and left hands of each subject can be regarded as the skillfulness of the right and left hand, it is proposed to define the degree of handedness of the subject based on the difference of these factor scores.

2. Test tasks based on haptic virtual reality

2.1 Outline of handedness evaluation system

An experimental system shown in Fig.1 has been developed for measuring the dexterity of a finger from the viewpoints of position control, force control, and manipulation of objects. The system consists of two force display devices (PHANToM OMNI), a display, and a computer for constructing a virtual task world. The specifications of the computer are shown in Table 1.

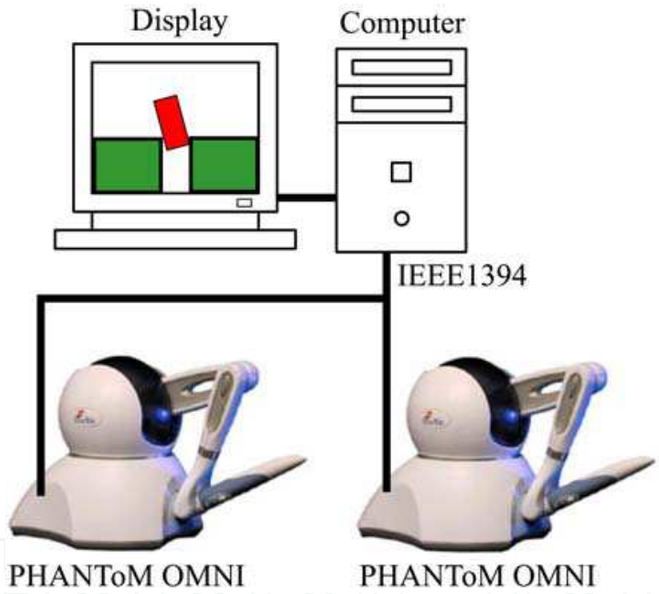


Fig. 1. System configuration

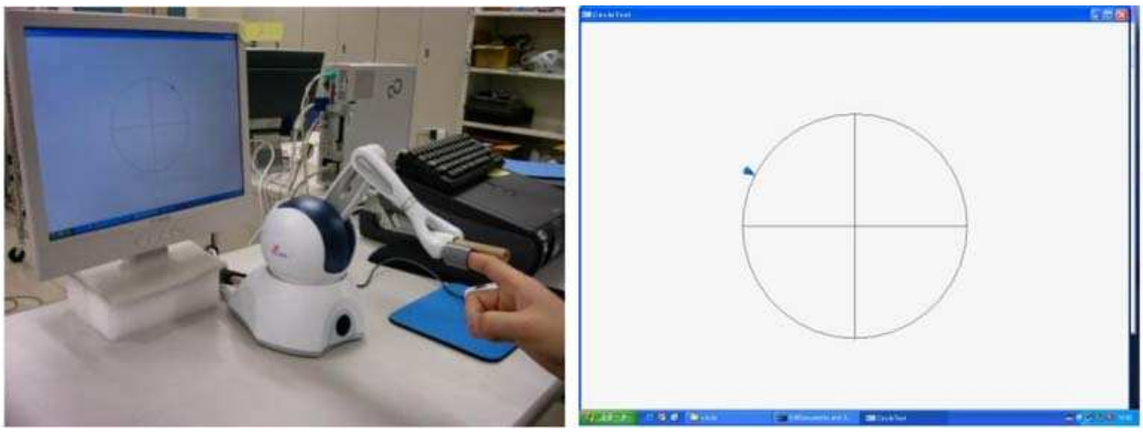
OS	Microsoft Windows XP Professional
CPU	Intel Pentium 4 3.2 [GHz]
Memory	1024 [MB]
Graphic Processor	nVidia GeForce6600
Bus Type	PCI Express × 16

Table 1. Specifications of computer

2.2 Position control test

This test is intended to measure the dexterity in positioning a fingertip accurately. The subject is asked to follow the desired point on the screen which moves along a circle with

constant velocity by using his/her index finger. The desired point turns around a circle six times taking 6 seconds for each turn. Fig.2-(a) shows the overview of the task environment and Fig.2- (b) shows the image on the monitor screen. Two tasks are prepared: One is with clockwise rotation and the other is counterclockwise rotation. This is to make the test fair to right-handed and left-handed subjects.



(a) Overview (b) Image on the monitor

Fig. 2. Position control test

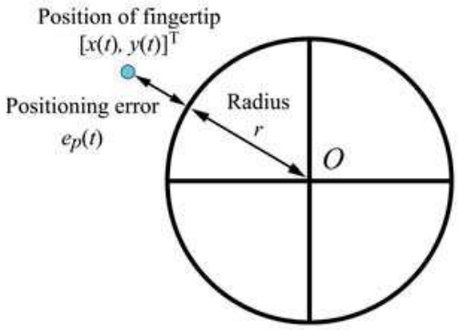


Fig. 3. Positioning error

The average of the tracking error during the five turns from the second to the last turn is taken as the measure of performance of this task. As is shown in Fig.3, the tracking error $e_p(t)$ at time t is given by

$$e_p(t) = |\sqrt{x^2(t) + y^2(t)} - r| \tag{1}$$

where $[x(t),y(t)]^T$ is the position vector of the fingertip on the virtual plane shown by small green circle and r is the radius of the circle. The measure of performance E_p is given by the average magnitude of tracking error, that is,

$$E_p = \frac{\int_0^T e_p(t)dt}{T} \tag{2}$$

where T is the total time (=30 [s]). The smaller the value E_p is, the more dexterous the subject is regarded in position control. A typical trajectory of the tracking error $e_p(t)$ of a subject is shown in Fig.4.

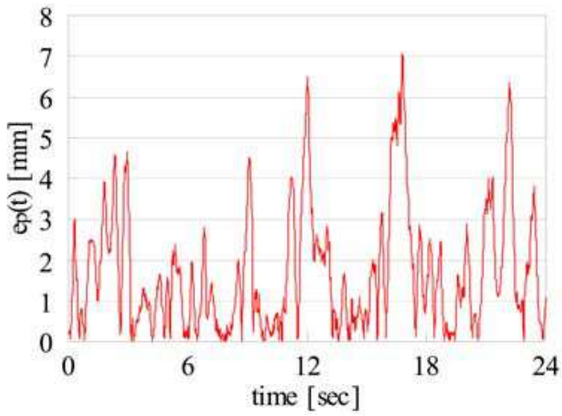
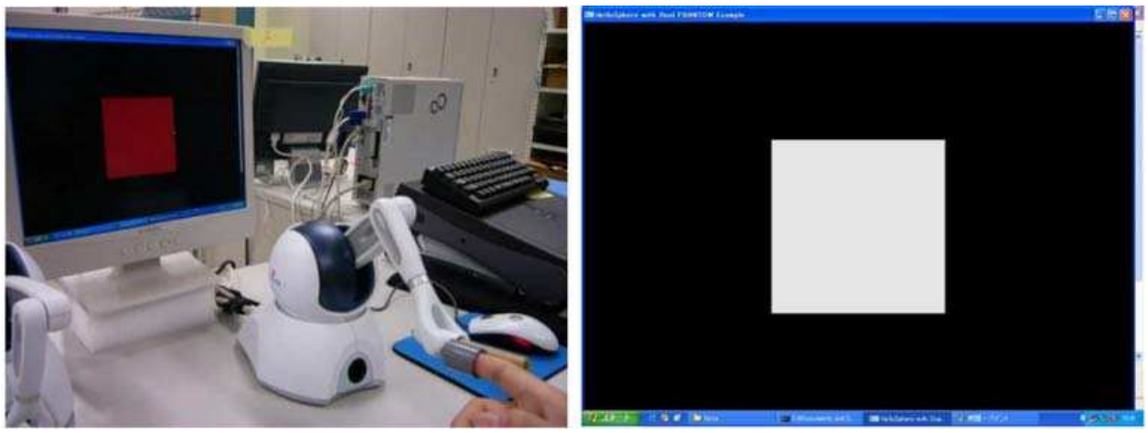


Fig. 4. A trajectory of measured positioning error

2.3 Force control test

This test is intended to measure the dexterity in exerting a certain desired force on an object by a fingertip accurately. The subject is asked to push a square box in the screen with a specified desired force. When the subject pushes the box, he/she can feel the reaction force through the force display device. The reaction force is calculated by using a spring-damper model of the surface of box. The subject can also watch the relative magnitude of the applied force $F(t)$ and the desired force F_d = 1.0[N] by the color of the box: The box becomes white when the applied force is close to the desired force ($|F(t) - F_d| \leq 0.1$[N]), it becomes red when the applied force is larger ($F(t) > 1.1$[N]), and green when it is smaller than the desired value ($F(t) < 0.9$[N]). The task continues ten seconds and the data is obtained during 1 through 10 seconds skipping the first 1 second. Fig.5-(a) shows the overview of the task environment and Fig.5-(b) shows the image on the monitor screen.



(a) Overview (b) Image on the monitor

Fig. 5. Force control test

The average of the force regulation error during the nine seconds is taken as the measure of performance of this task. The force regulation error at time t is given by

$$e_f(t) = |F(t) - F_d| \tag{3}$$

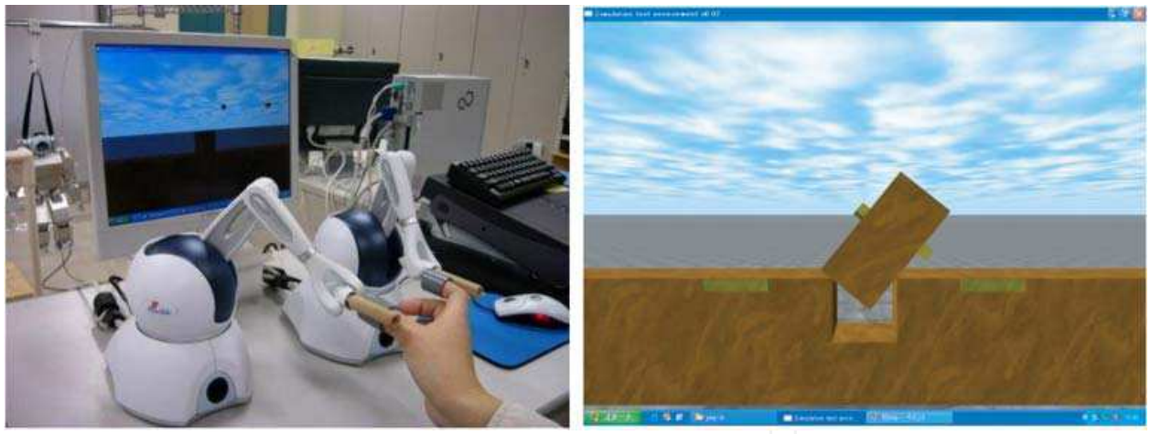
and the measure of performance E_f is given by

$$E_f = \frac{\int_0^T e_f(t)dt}{T} \tag{4}$$

where T is the total time (=9 [s]). The smaller the value E_f is, the more dexterous the subject is regarded in force control.

2.4 Manipulation test

This test is intended to measure the dexterity of a subject in manipulating objects by his/her hand. The subject is asked to insert a peg into a hole in virtual world, which is constructed by using a dynamics simulator OpenDynamicsEngine. The interaction forces among the fingertips, peg, and hole are calculated based on the intrusion distance among them following the approach described in Yoshikawa & Yoshimoto (2000). The gravitational acceleration is assumed to be 9800[mm/s²]. The task is specified in the two-dimensional space by constraining the motion of peg in a plane parallel to the monitor screen. The subject is asked to pick up a peg of 50[mm] wide, 100[mm] long, and weighing 100[g], by his/her thumb and index finger and to insert it into a hole of 50[mm] deep and 51[mm] wide, and then to return it to the original position. Fig.6-(a) shows the overview of the task environment and Fig.6-(b) shows the image on the monitor screen. Two tasks are prepared to make a fair evaluation regarding the initial position of the peg: right and left initial positions (see Fig.7). The time E_m[s] needed to perform this insertion task once is taken as the measure of performance.



(a) Overview (b) Image on the monitor

Fig. 6. Manipulation test

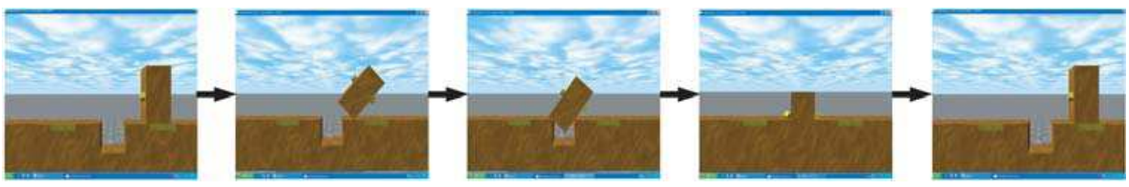


Fig. 7. Peg insertion task from right initial position

3. Experimental results

Ten male subjects of age 22–23 have taken the above described tests. According to the conventional LQ test, nine subjects (Subjects A through I) were right-handed and one subject (Subject J) was left-handed (see Table 2). Tests were repeated three times for the right and left hands of each subject and their averages were regarded as the measured performance data denoted as $\{Z_{ihp}, Z_{ihf}, Z_{ihm}\}$, where subscript i means subject $i = A, B, \ldots, J$, subscript h means left hand ($h = l$) or right hand ($h = r$), and subscripts p, f and m mean the position control, force control, and manipulation tests, respectively. Table 3-5 and Fig.8 show the measured data. From the figure it can be seen that, for the nine subjects except subject J, the performance of the right hand was better than the left hand in the position control test and manipulation test. For subject J the left hand was better than the right hand. This is consistent with the result of LQ test.

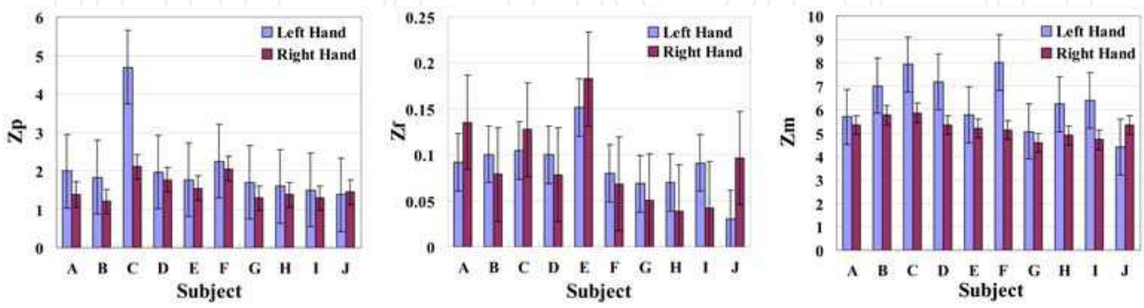
On the other hand, in the force control test, the left hands of subject J and three others performed better than their right hands.

The correlation matrix R of the performance data in Fig.8 for the three tests is calculated as

$$R = \begin{bmatrix} 1 & 0.189 & 0.657 \\ 0.189 & 1 & 0.279 \\ 0.657 & 0.279 & 1 \end{bmatrix} \tag{5}$$

Subject	LQ value
A	100
B	100
C	100
D	100
E	100
F	100
G	100
H	100
I	90
J	-100

Table 2. Results of LQ value



(a) Position control test (b) Force control test (c) Manipulation test

Fig. 8. Results of the three tests

	Left hand (Z_{ilp})		Right hand (Z_{irp})	
	L. T.	R. T.	R. T.	L. T.
A	2.073	1.911	1.480	1.287
B	1.409	2.246	1.153	1.242
C	4.112	5.268	2.263	1.935
D	1.794	2.117	1.767	1.758
E	1.999	1.529	1.432	1.657
F	2.128	2.368	2.051	2.053
G	1.616	1.778	1.258	1.318
H	1.364	1.842	1.448	1.308
I	1.511	1.483	1.243	1.333
J	1.285	1.469	1.364	1.525

Table 3. Results of the position test [mm] (Note: L. T.: left turn, R. T.: right turn. Z_{ilp} and Z_{irp} are given by the means of the values for L. T. and R. T.)

	Left hand (Z_{ilf})	Right hand (Z_{irf})
A	0.0919	0.1355
B	0.1005	0.0787
C	0.1046	0.1276
D	0.0999	0.0785
E	0.1516	0.1828
F	0.0799	0.0681
G	0.0685	0.0501
H	0.0698	0.0385
I	0.0912	0.0422
J	0.0303	0.0965

Table 4. Results of the force test [N]

	Left hand (Z_{ilm})		Right hand (Z_{irm})	
	L. S.	R. S.	R. S.	L. S.
A	6.035	5.344	5.299	5.393
B	6.787	7.254	6.246	5.271
C	7.516	8.341	6.101	5.610
D	8.035	6.319	5.209	5.471
E	5.956	5.594	5.259	5.126
F	7.974	8.057	4.903	5.343
G	4.864	5.266	4.736	4.429
H	5.505	6.954	4.674	5.114
I	5.783	6.998	4.936	4.507
J	4.741	4.067	5.683	5.009

Table 5. Results of manipulation test[s] (Note: L. S.: initial position on left side, R. S.: initial position on right side. Z_{ilm} and Z_{irm} are given by the means of the values for L. S. and R. S.)

From this result, it is seen that the correlation between the position and manipulation tests is large but the correlation between the force test and the other tests is small, implying that the dexterity on force control has a little different tendency from that of position control and manipulation.

4. Definition and evaluation of handedness and dexterity

It is desirable to establish a general quantitative evaluation method of handedness. We propose a quantitative definition of the handedness based on the factor analysis. At the same time, a definition of dexterity for each hand and for each person is also proposed.

To analyze the obtained data by the factor analysis, we first standardize the measured performances for each test as follows. The standardized value z of datum Z is given by

$$z_{iht} = \frac{Z_{iht} - \overline{Z}_t}{v_t}, \quad t = p, f, m \tag{6}$$

where $\overline{Z}_t$ and v_t are, respectively, the average and the standard variation of the data $\{Z_{iht}\}$ for a fixed t.

Let the standardized performance data for hand h of subject i for the position control test be z_{ihp}, that for the force control test be z_{ihf}, and that for the manipulation test be z_{ihm}. Then from the basic formula of the factor analysis we adopt the one-factor model given by

$$z_{ihp} = a_p d_{ih} + e_{ihp} \tag{7}$$

$$z_{ihf} = a_f d_{ih} + e_{ihf} \tag{8}$$

$$z_{ihm} = a_m d_{ih} + e_{ihm} \tag{9}$$

where d_{ih} is the factor score, a_p, a_f, a_m are the factor loading coefficients for the three tests, and e_{ihp}, e_{ihf}, e_{ihm} are the independent errors.

In order to calculate the factor score we first obtain the values of factor loadings. Let the factor loading matrix A be

$$A = [a_p \;\; a_f \;\; a_m]^T \tag{10}$$

then the relation between A and the correlation matrix R is given by

$$R = AA^T + R_e \tag{11}$$

where R_e is the diagonal covariance matrix of the independent errors. Using the Principal Factor Method, factor loading matrix A satisfying (11) is given by

$$A = [-0.668 \;\; -0.284 \;\; -0.984]^T \tag{12}$$

Now we can obtain the factor score d_{ih} based on the relation

$$d_{ih} = [z_{ihp} \;\; z_{ihf} \;\; z_{ihm}]R^{-1}A \tag{13}$$

Note that, although matrix $-A$ can also be a solution of (11), the above solution with negative components was intentionally chosen. This way, we can obtain the factor score such that the larger the factor score is, the more dexterous the subject is.
The factor scores of the right and left hands of each subject are given in Table 6 and in Fig.9.

Subject	Factor score		Dexterity d_i	Handedness h_i	LQ
	d_{il}	d_{ir}			
A	0.087	0.429	0.258	0.171	R
B	-1.157	0.065	-0.545	0.611	R
C	-2.156	-0.083	-1.120	1.036	R
D	-1.310	0.429	-0.440	0.870	R
E	0.002	0.553	0.278	0.275	R
F	-2.107	0.621	-0.743	1.364	R
G	0.694	1.172	0.933	0.239	R
H	-0.395	0.878	0.241	0.636	R
I	-0.546	1.044	0.249	0.795	R
J	1.340	0.436	0.888	-0.452	L

Table 6. Evaluation results of dexterity and handedness

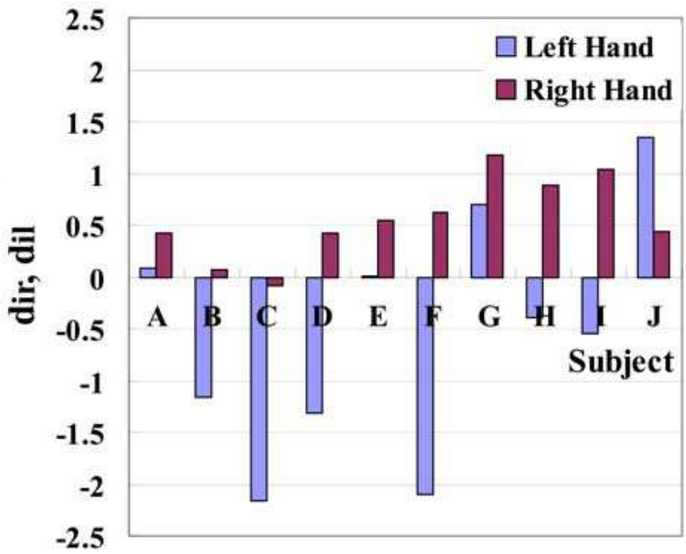


Fig. 9. Factor scores

Based on the above considerations, we define the dexterity d_i and handedness h_i of a subject using the factor score of his/her right hand d_{ir} and left hand d_{il}:

$$d_i = \frac{d_{ir} + d_{il}}{2} \tag{14}$$

$$h_i = \frac{d_{ir} - d_{il}}{2} \tag{15}$$

The dexterity is shown in Fig.10. The handedness and the LQ value of each subject are shown in Fig.11. From the figure we can see that when the value of handedness is positive, the LQ value is also positive, and vice versa, implying that the value of handedness h_i and the conventional LQ value do not contradict to each other. The calculated degrees of handedness, however, differ largely among the right-handed subjects. From this result, it is expected that the proposed method can be used for more detailed quantitative evaluation of handedness.

5. Conclusion

A quantitative evaluation method of dexterity and handedness of a person based on the factor analysis of data from three kinds of performance tests in haptic virtual space has been proposed.

Result of the judgment of handedness from our method for the ten subjects was consistent with that from the conventional LQ method. Hence the proposed approach can be a useful quantitative evaluation method. However, the number of subjects was just ten which is very small. The validity of the method should be examined through tests for a larger group of subjects.

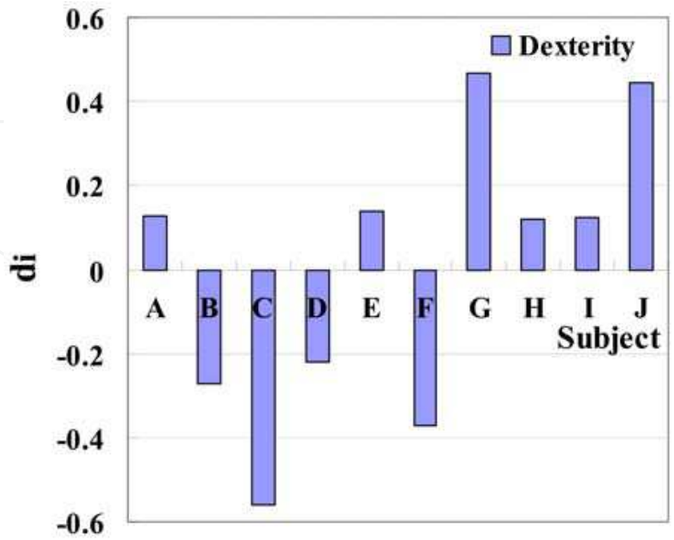


Fig. 10. Dexterity

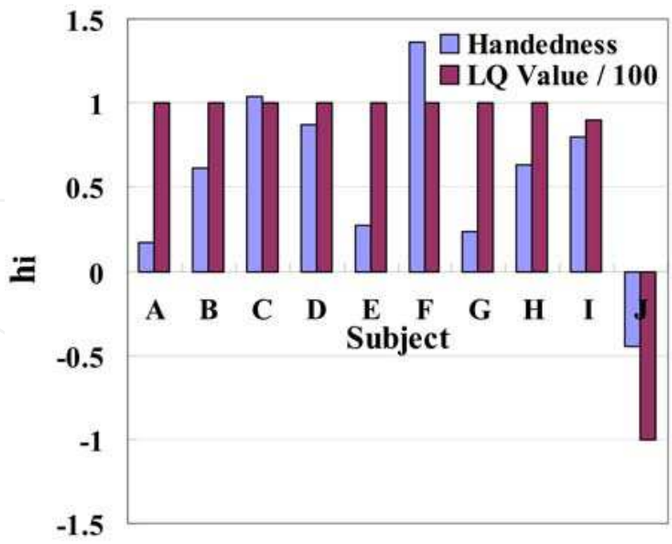


Fig. 11. Handedness

The tendency of force test was a little different from the other two tests. The reason for this difference should be studied in the future.

This chapter has been written based on paper "A Quantitative Evaluation Method of Handedness Using Haptic Virtual Reality Technology" that was presented at the 16th IEEE International Symposium on Robot & Human Interactive Communication, (IEEE RO-MAN 2007, Jeju, Korea, August, 2007).

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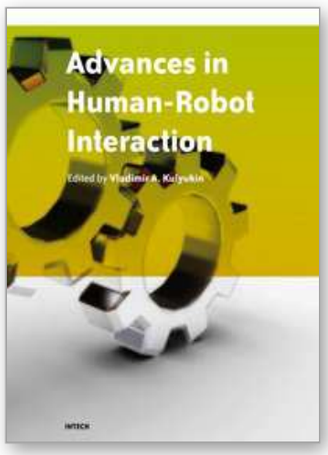
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Rapid advances in the field of robotics have made it possible to use robots not just in industrial automation but also in entertainment, rehabilitation, and home service. Since robots will likely affect many aspects of human existence, fundamental questions of human-robot interaction must be formulated and, if at all possible, resolved. Some of these questions are addressed in this collection of papers by leading HRI researchers.

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