Personal Identification Method for Robot with Whole–Body Sensing Mechanism

Junichi Arakawa, Toshiaki Tsuji
Saitama University
tsuji@ees.saitama-u.ac.jp

Desney S. Tan
Microsoft Research

Abstract- Haptic modality is one of the most important issues in man–machine communication. This paper introduces a personal identification technique based on force information of finger tracing that can be used for advanced man–machine communication systems. Compared to other biometric methods, the proposed method has an advantage of high security due to the invisible feature of force information. Experimental results show the validity of the proposed method.

I. Introduction

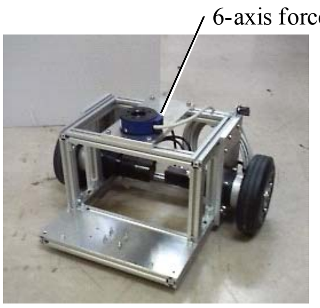
In recent years, many human–support robots have been developed that employ advanced motion control technology. However, these robots operate in close contact with people and thus may contact or collide with people. To prevent this, some researchers have developed a whole–body haptic sensing mechanism for robots to enable them to detect contact or collisions with people [1]. Of the many communication modalities for man–machine systems, haptic modality is promising for allowing a person to communicate their intentions or feelings to a robot that is within a touchable distance. A robot equipped with a whole–body haptic sensor can communicate with a person using haptic sensing motions [2]. Our research group has proposed a method that enables a robot to recognize commands by a person tracing their finger on the surface of the robot [3]. A signal transferred by haptic sensing contains a lot of useful information and thus haptic sensing can advance man–machine communication. In this paper, we propose a personal identification technique based on haptic sensing as an example of a method for extracting valid data using haptic sensing.

This personal identification method allows a robot equipped with a whole–body haptic sensor to identify a person if he/she touches any part of the robot's body for a few seconds. This personal identification uses invisible force information via haptic sensing so that it also has the potential to be used in security systems. Biometric identification utilizing personal body data is being considered for general personal identification methods [4,5]. However, visual information based on fingerprints, irises, faces, hand geometry, and veins obtained using specially designed cameras or scanners and auditory information for voice verification can be copied using existing techniques enabling such personal body data to be stolen [6]. Identification based on the force a person applies when writing has been well studied [7,8]. A pen or a tablet that can detect the strength of pen strokes can be used to obtain identification information when a person signs their signature. However, this technique requires a device that can sense the strength of a pen stroke. An identification method that uses a robot equipped with a haptic sensor is more convenient because people can make direct contact with the robot and do not require a writing implement. Identification based on haptic information also has a merit that it is difficult to reproduce because haptic identification utilizes invisible information that is transferred by contact. It is expected that an identification method employing haptic communication can also be used to develop technology for advanced man–machine communication systems. This paper describes a system that allows a robot to identify a person when they trace their finger on the surface of robot. It also assesses the effectiveness of personal identification by a robot based on haptic information.

II. Overview of Haptic Sensor

A. Structure of experimental system

Fig. 1 shows photographs of a robot on which a shell–like haptic sensor "haptic armor[9]" is installed. This sensor consists of an end effector and a sensor. The end effector is made from simple parts such as molded plastic. It attaches only to the force sensor and does not contact the other parts of the robot. All external forces are transferred through the end effector to the sensor device. The sensor is a six–axis force sensor. The end effector is constructed by connecting five 3-mm-thick acrylic plates to form a cube that completely covers the sensor except its base since its wheels run on the ground. The end effector is attached through a support to the six–axis force sensor on the mobile robot. The ratios of the rigidity



a) main body and sensor device

b) covered by end-effector

Fig. 1. Experimental setup

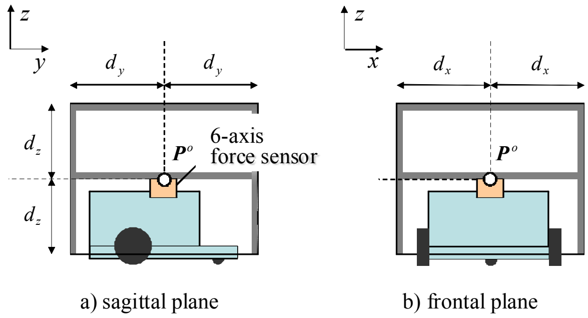


Fig. 2. Mechanism of haptic armor

Table 1. Parameters of experimental system

G_r	Reduction ratio	1/33	
w^c	Weight of end-effector	4.4	[kg]
d_r	Radius of wheels	75	[mm]
d_x, d_y, d_z	Distance from center to surface of end-effector	250	[mm]
d_w	Half tread	205	[mm]

and the viscosity to the end effector mass are high enough and the natural mechanical frequency is rapidly damped.

The haptic sensor is termed "haptic armor" because it functions both as an outer shell that covers the robot and as a force detector. Fig. 2 shows the configuration of the experimental system and Table 1 lists its parameters.

B. *Method for Calculating Contact Information*

Next, we explain the method used for calculating contact information (external force vector and point of application) from the response of the six–axis force sensor of haptic armor. Since the end effector transfers all external forces to the six–axis force sensor and the forces are in equilibrium, we obtain the following equations:

$$\boldsymbol{F}^e + \boldsymbol{F}^o = \boldsymbol{0}, \qquad (1)$$

$$\boldsymbol{F}^e \times \left(\boldsymbol{P}^e - \boldsymbol{P}^o\right) + \boldsymbol{M}^o = \boldsymbol{0}, \qquad (2)$$

where $\boldsymbol{P^e}$ is the position of the contact point, $\boldsymbol{F}$ is the force vector, $\boldsymbol{M}$ is the moment vector, the superscript e indicates external force and the superscript o indicates operation at the support point. The sensor position $\boldsymbol{P^o}$ is determined by the dead reckoning method and $\boldsymbol{F^o}$ and $\boldsymbol{M^o}$ are calculated from the force sensor data. Equation (2) can be expanded as:

$$\begin{aligned} M_x^o &= F_z^e\left(P_y^e - P_y^o\right) - F_y^e\left(P_z^e - P_z^o\right) \\ M_y^o &= F_x^e\left(P_z^e - P_z^o\right) - F_z^e\left(P_x^e - P_x^o\right) \\ M_z^o &= F_y^e\left(P_x^e - P_x^o\right) - F_x^e\left(P_y^e - P_y^o\right) \end{aligned} \quad . \qquad (3)$$

P_z is calculated as follows:

$$\begin{aligned} P_z^e &= \frac{-M_x^o - F_z^e P_y^o}{F_y^e} + P_z^o + \frac{F_z^e}{F_x^e} P_y^e \\ &= \frac{-M_y^o - F_z^e P_x^o}{F_x^e} + P_z^o + \frac{F_z^e}{F_y^e} P_x^e \end{aligned} \quad . \qquad (4)$$

Equation (4) indicates that $\boldsymbol{P^e}$ is on a straight line parallel to $\boldsymbol{F^e}$. If the external shape of the robot is already known, $\boldsymbol{P^e}$ can be determined by calculating the point of intersection between the external surface of the robot and the straight line given by (4). The external shape of the robot is often complicated and consists of multiple planes. The following equation expresses the external shape of a robot composed of p curved planes:

$$f_k\left(\boldsymbol{P^e}\right) = 0 \qquad (k=1, 2, \ldots, p) \quad . \qquad (5)$$

When the external shape of robot is convex, there are two intersection points between the straight line created by (4) and the curved planes composed by (5). Assuming that the force acts only in the direction that the external shape of robot is pressed, one of the two intersection points will be the point at which the external force was applied. When the external shape of robot is convex, there will be only one point of $\boldsymbol{F^e}$ that acts from outside to inside. This principle is used to determine the contact point from the response of the six–axis force sensor. Haptic armor, which can determine both the external force vector and the point the external force acts, can perform haptic sensing for one point of contact.

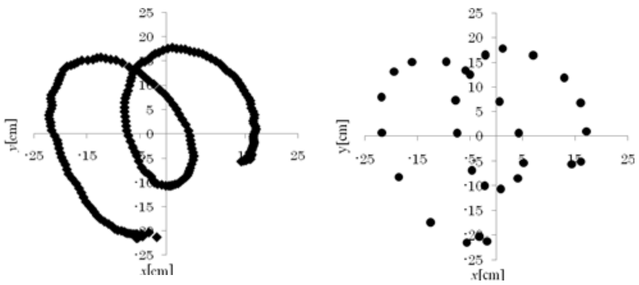
III. Personal Identification through Finger Tracing on Robot Surface

The method proposed in this paper compares finger tracing data on the external surface of the robot with preregistered data. A dynamic programming (DP) matching method compares the preregistered data with an unknown person's contact trajectory and force against the robot and calculates the similarity between these data sets. When the similarity exceeds a specified level, the person is identified as the registered person.

This study presents a method for detecting the position of the contact point and the external force. When a person traces their finger on the surface of robot, information is recorded concerning the contact point and the external force. This information is then processed to determine the finger trajectory, finger speed, and contact force. A method for extracting characteristics that identify a person from the obtained information is described below.

A. *Extraction of Characteristics from Traced Trajectory*

The characteristic points are extracted from the contact-point coordinate system that is read out from the haptic armor at a constant rate. The method used for character recognition [10] is used to extract the trajectory characteristics. First, the start and end points of the traced trajectory are used as characteristic points. Next, from the contact points between adjacent characteristic points, the point that is located furthest from the straight line connecting the two characteristic points and that exceeds the threshold value is regarded as a characteristic point. This process is repeated until the point furthest from the straight line becomes less than the threshold value. Fig. 3 shows the extraction of characteristic points of a subject's contact trajectory.



(a) before extraction (b) after extraction

Fig. 3. Extraction of characteristic points

B. Extraction of Characteristic Quantities from Force Data

The force a person applies when pressing an object has a high variability. The experimental results using haptic armor also shows a low reproducibility, as evidenced by the large difference between the maximum force. Fig. 4 shows the maximum force applied when 3 subjects traced their fingers on the surface of a robot 10 times and when they repeated the action after an interval of one week. Each subject exhibited a variance of 10 N irrespective of the sequence of the experiments. The subjects tended to apply higher forces in the second experiment after an interval of one week. For this reason, we decided to normalize the measured force. Thus, we divided the applied force into multiple levels such that the highest level corresponds to the maximum applied force. The points that the applied force in the levels change are extracted as the characteristic quantity. Fig. 5 shows how force characteristic points are extracted from a subject's force data.

C. DP Matching Method

To control fluctuations with time, the DP matching method performs nonlinear scaling of the time axis of the input data for the template data, which enables optimum identification [11,12]. This experiment uses the DP matching method for the traced–trajectory coordinate system and for force data.

The time axis of the time series data is scaled so that input data plotted on the time axis i completely conforms to the registered data plotted on the time axis j. The scaled time axis is displayed using $i(t)$ and $j(t)$ $(t = 1, 2, \cdots, T)$. The

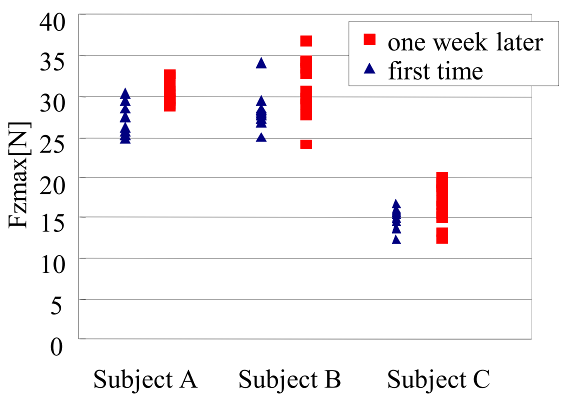
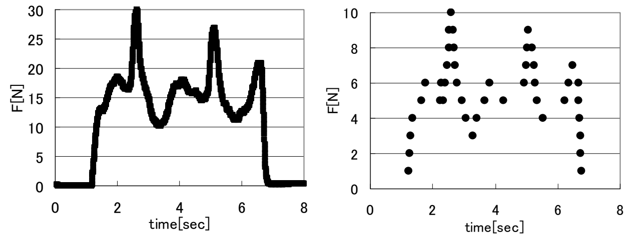


Fig. 4. Repeatability of force information



(a) before extraction b)after extraction

Fig. 5. Extraction of force characteristic points

distance between the two points $i(t)$ and $j(t)$ at time t is used to represent the distance between data points.

The distance between data is defined as follows:

$$D = \min\left[\sum_{t=1}^{T} d\big(i(t), j(t)\big)\right] \quad . \tag{6}$$

The quantity $d(i, j)$ is the distance between the ith input data and the jth registered data. Assuming that the start and end points of input data conform to those of registered data (i.e., "$i(t) = 1$" to "$j(t) = 1$" and "$i(T) = I$" to "$j(T) = J$") and that time is not reversed by using a scaled time axis (i.e., $i(t)$ and $j(t)$ are monotonically increasing functions), we solve the following minimum problem for the optimum cumulative distance $g(i, j)$.

First, the initial condition for $g(i, j)$ is:

$$g(1, 1) = d(1, 1) \tag{7}$$

The recurrence equation is:

$$g(i, j) = d(i, j) + \min\begin{cases} g(i, j-1) + w \\ g(i-1, j-1) \\ g(i-1, j) + w \end{cases} \tag{8}$$

$$i = 1, 2, \cdots, I, \quad j = 1, 2, \cdots, J$$

where w is a penalty for the scaled time. The distance D is calculated using:

$$D = \frac{g(I, J)}{T} \tag{9}$$

This distance D is a measure of the similarity between the signals.

IV. Experimental Verification

A. Extracting Characteristic Points of Traced Trajectory

Seven subjects were asked to trace their finger on the surface of the robot and we recorded their contact trajectories and the force variation on the surface of robot. Fig. 6 shows a photograph of the experiment. Each subject performed the same action 10 times. The first trace was regarded as registered data and it was compared with the subsequent 9 traces, which were treated as input data. In addition, 10 more traces were obtained after one week and these data were compared with the initially registered data to check the reproducibility of traces. Figs. 7 and 8 show the obtained traced trajectories and temporal force variations, respectively.

Fig. 6. Image of experiment

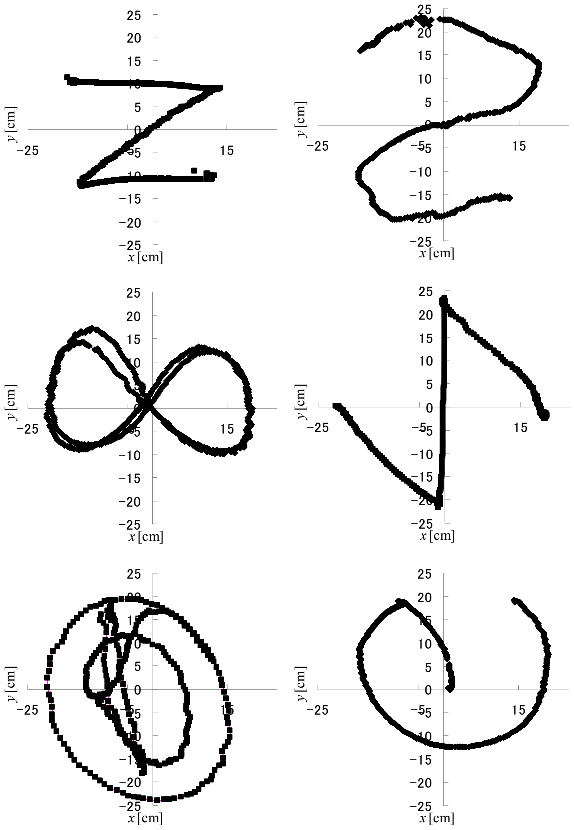


Fig. 7. Contact trajectories of subjects

Figs. 9 and 10 show the results of comparing the registered data with the input data using the DP matching method. The vertical axes of the graphs indicate the distance parameter D calculated using the DP matching method. Fig. 9 shows the result of the distance D calculated by the following equation:

$$d(i, j) = \left| \boldsymbol{P}^i(i(t)) - \boldsymbol{P}^r(j(t)) \right| \tag{10}$$

where $\boldsymbol{P}^i(i(t))$ denotes contact position of input data at scaled time $i(t)$, and $\boldsymbol{P}^r(j(t))$ denotes that of registered data at scaled time $j(t)$. On the other hand, Fig. 10 shows the result of the distance D calculated by the following equation:

$$d(i, j) = \left| F_z^i(i(t)) - F_z^r(j(t)) \right| \tag{11}$$

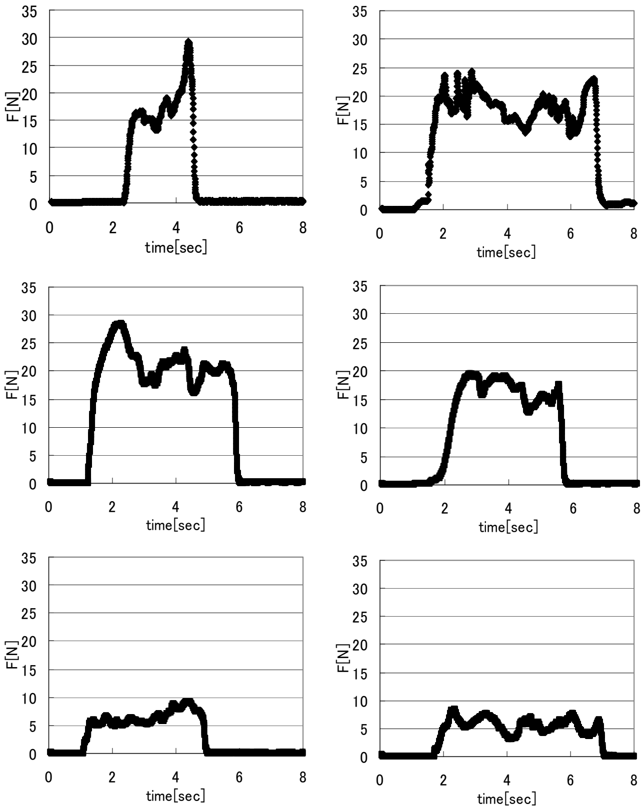


Fig. 8. Force responses of subjects

where $F_z^i(i(t))$ and $F_z^r(i(t))$ denote vertical force of input and registered data, respectively. Both of them are normalized into 10 levels. The smaller D is, the greater the similarity between the compared signals. The horizontal axes indicate the compared data. These figures show comparisons between data for the same person on the same day, the same person after one week, and different people. The reproducibility of data input after one week interval was high enough compared with data input on the same day; this confirms that the reproducibility of the tracing motion does not deteriorate within one week. In Fig. 9, the distance D for the same subject differs from that of the other two subjects for the same trajectories, which demonstrates that selecting an appropriate threshold will permit the results for different people to be distinguished.

The DP matching results of contact trajectory reveal that the subjects can be identified by setting a threshold value of 5.0. However, the DP matching results of force response indicate little difference between the data for the same subject and the data for the other two subjects. In addition, Fig. 8 shows high similarities in the vertical force patterns when the subjects trace their fingers on the surface of the robot. These results show the difficulty to identify a person based on the vertical force. However, a position-based identification without force information may end up to a low security identification vulnerable to imitation.

Therefore, we performed several experiments to search a way for force-based identification. In this experiment, the

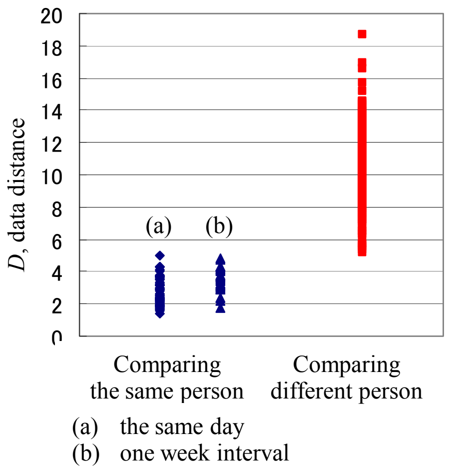


Fig. 9 DP matching results of contact trajectory

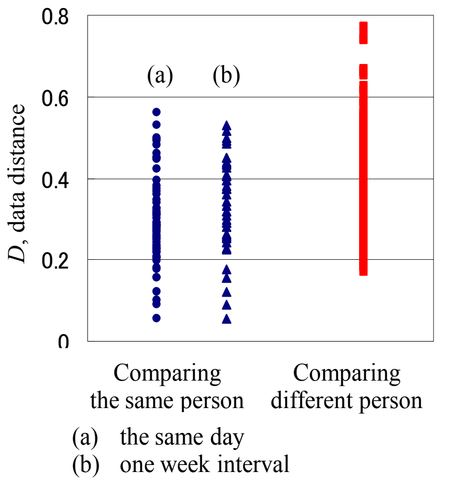


Fig. 10 DP matching results of force response

subjects were allowed to modify the force they applied while they are forced to trace the same trajectory.

B. Personal Identification using Force Information Only

We confirmed that personal identification was possible by conducting experiments in which 3 subjects traced their fingers along the same trajectory (a circle) on the surface of the robot. In this experiment, the subjects were asked to produce specific patterns of force. They repeated the same action 10 times. Each of the traces was compared with the other 9 traces given by own self and 20 traces given by others.

Fig. 11 compares the vertical force data obtained. There is a difference between the distance D of data obtained for the same subject and that of the other subjects and it is possible to identify the subjects to some degree. The threshold value that is used to determine whether a person is the preregistered one is set to the maximum distance between the own 10 traces. Experimental result shows the false acceptance rate is 16.7% (100/600). Note that false rejection rate is necessarily 0% in this experiment. These results indicate that personal identification based on comparing vertical force data needs to be improved before it can be used in practical applications. Therefore, another experiment was performed that compared force vectors. The following equation is used to calculate the distance D instead of (11):

$$d(i, j) = \left| \boldsymbol{F}^i(i(t)) - \boldsymbol{F}^r(j(t)) \right|. \tag{12}$$

Here, $\boldsymbol{F}^i(i(t))$ and $\boldsymbol{F}^r(j(t))$ are normalized force vectors of input and registered data, respectively. Fig. 12 shows the comparison results. When the threshold value is set to the maximum distance between the own 10 traces, the false acceptance is 0.2% (1/600). These results demonstrate that comparison of the force vector makes it possible to identify a person with a high reliability.

C. Discussion

We have demonstrated that a person can be identified based on contact trajectory and force variation data. Personal identification based on vertical force data shows a low rate of identification. Such algorithm is similar to conventional methods for handwriting analysis. The identification rate highly improves by comparing force vector information. Although maximum and average forces of a person highly vary after time interval, normalized force information of a person has high reproducibility.

Haptic sensing reveals a lot of information besides the contact trajectory and the force vectors used in the present experiments. Variations in the force vector, finger tracing speed and the movement direction are the examples of candidates. Further investigation on these candidates and detailed evaluation with larger number of subjects are our future works.

V. Conclusion

This paper proposes a personal identification method that allows a robot with a haptic sensor to identify people. We confirmed that a robot could identify a person who traced their finger on the surface of the robot. The robot extracted the characteristics of a person that allowed them to be identified from information such as trajectory and force variations when they touched the surface of the robot. Experiments demonstrated that a person could be identified through contact trajectories and force variations, which confirms the effectiveness of personal identification by a robot using haptic information.

Acknowledgment

This project is supported in part by Microsoft Research IJARC Blue Sky Project.

References

[1] H. Iwata and S. Sugano: "Whole-body Covering Tactile Interface for Human Robot Coordination," *Proc. of the IEEE Int. Conf. Robotics and Automation*, pp. 3818-3824, (2002).

[2] T. Miyashita, T. Tajika, H. Ishiguro, K. Kogure, and N. Hagita: "Haptic Communication between Humans and Robots," *Proc. of 12th Int. Symp. Robotics Research*, (2005).

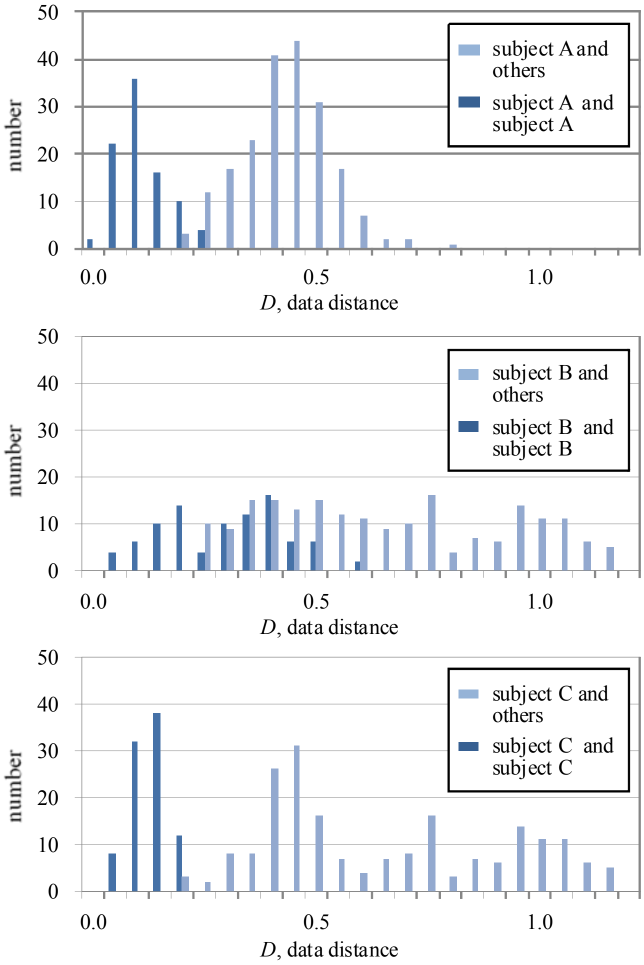


Fig. 11. Data distance of vertical force when subjects input the same trajectory

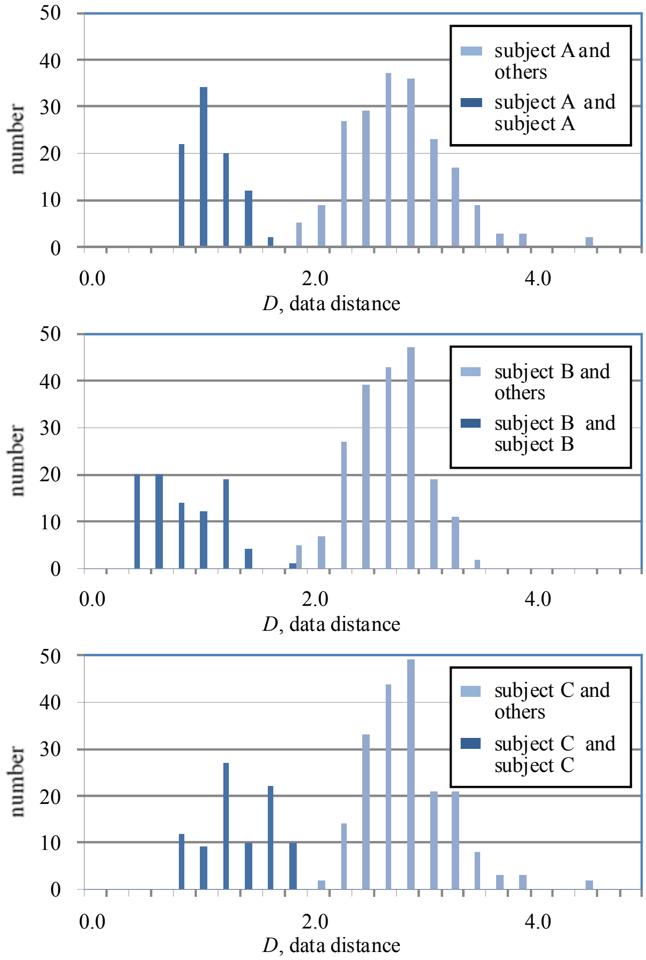


Fig. 12. Data distance of force vector when subjects input the same trajectory

[3] T. Tsuji, T. Ito: "Command Recognition of Robots Based on Feature Quantity Extraction from Haptic Information," *Journal of Robotic Society Japan*, Vol. 28, No. 3, pp. 79-86, (2010) (in Japanese).

[4] K. Uchida: "The State-of-the-art of Fingerprint-Based Personal Identification," *ITE Journal*, Vol. 55, No. 2, pp. 176-179, (2001) (in Japanese) .

[5] A. Hoover, V. Kouznetsova, and M. Goldbaum, "locating blood vessels in retinal image by piece-wise threshold probing of a matched filter response," *IEEE Trans. Med. Imaging*, Vol. 19, No. 3, pp. 203-210, (2000).

[6] M. Une, A. Otsuka, and H. Imai, "Wolf Attack Probability: A Theoretical Security Measure in Biometric Authentication Systems," *IEICE Trans. Inf. & Syst.*, Vol. E91-D, No. 5, pp. 1380–1389, (2008) (in Japanese).

[7] R. Plamondon and G. Lorette, "Automatic Signature Verification and Writer Identification-The State of the Art," Pattern Recognition, vol.22, no.2, pp.107-131,(1989).

[8] Y. Yamazaki and N. Komatsu, "Extraction of Personal Features form On-line Handwriting Information in Context-independent Characters," *IEICE Trans. Fundamentals*, Vol. E83-A, No. 10, pp. 1955-1962, (2000).

[9] T. Tsuji, Y. Kaneko, S. Abe: "Whole-body Force Sensation by Force Sensor with Shell-shaped End-effector," *IEEE Trans. on Industrial Electronics*, Vol. 56, No. 5, pp.1375-1382, (2009).

[10] K. Akiyama, M. Nakagawa: "A Linear-Time Elastic Matching Algorithm for On-line Recognition of Handwritten Japanese Characters", *IEICE Trans. D-II* Vol.J81-D-II No.4, pp.651-659, (1998) (in Japanese).

[11] S. B. Needleman and C. D. Wunsch: "A General Method Applicable to the Search for Similarities in the Amino Acid Sequence of Two Proteins" *Journal of Molecular Biology*, Vol. 48, pp.443-453, (1970).

[12] T. Ito, T. Tsuji: "Command Recognition of Robot with Low Dimension Whole-Body Haptic Sensor," *Trans. IEE Japan*, Vol. 130-D, No. 3, 293-299, (2010) (in Japanese).

[13] L Ma, T Tan, Y Wang, D Zhang: "Personal Identification Based on Iris Texture Analysis,"*IEEE Trans. Pattern Analysis and Machine Intelligence,* Vol. 25, No. 12, (2003).

[14] W. Shu, D. Zhang: "Automated personal identification by palmprint," *Optical Engineering*, Vol. 37, 2359, (1998).

[15] K. B. Reed, M. Peshkin, M. J. Hartmann, J. Patton, P. M. Vishton, M. Grabowecky: "Haptic Cooperation Between People, and Between People and Machines," *Proc. of the IEEE Int. Conf. Intelligent Robots and Systems*, pp. 2109-2114, (2006).

[16] M. S. Dulberg, R. St. Amant, L. S. Zettlemoyer : "An Imprecise Mouse Gesture for the Fast Activation of Controls," *Proc. INTERACT'99*, pp. 375-382, (1999).

[17] J. Arakawa, T. Tsuji: "Personal Identification of Robot with Whole-body Haptic Sensor," *The Papers of Technical Meeting on Industrial Instrumentation and Control, IEE Japan*, IIC-10-082, (2010) (in Japanese).