Extraction of precise tactile-motion patterns from in-hand manipulation using data glove with high-density tactile sensors

Ryo Wakatabe, Yasunori Yamada, Takashi Sagisaka, Yoshiyuki Ohmura and Yasuo Kuniyoshi

***Abstract*—To investigate human manipulation, researchers have measured human hand motions and tactile inputs. Tactile measurements of a precision grip by recording tactile nerves have revealed a detailed temporal relation between tactile afferents and gripping force. Recently, data gloves have enabled us to measure manipulations conducted using the whole hand. However, analyses of data gloves with higher spatial resolutions can improve the range of observation. In this pape, using a data glove with high spatiotemporal resolutions and analyses to select tactile-motion variables particularly addressing precision, we extracted precise tactile points (PTPs) and precise motions (PMs) from a rotating cylinder manipulation. The PTPs are selected such that tactile points are active with high repeatability over trials and their active timings have low variance. In addition, the PMs are selected such that motions appear with high repeatability over trials and their timings have low variance. Results showed that PTPs and PMs are localized both spatially in the hand and temporally in the task. Moreover, patterns of PTPs and PMs extracted by two manipulations of cylinders were compared with different centers of mass obtained with identical regrasping procedures. We therefore suggest that patterns of PTPs and PMs characterize precise differences of manipulations that are indistinguishable by previous analyses.**

I. Introduction

Controlling in-hand manipulation with a multi-fingered robotic hand remains a major theme in robotics. Although a controller for in-hand manipulation is achieved analytically based on hybrid system theory, this cannot compute control input in real-time [11]. In contrast, human hands can manipulate dexterously. To investigate how human hands manipulate objects might contribute to a controller of a robotic hand.

Physiological studies have revealed tactile-motion control in a precision grip. Human hands adjust fingertip forces to the local frictional condition detected by tactile mechanoreceptors to avoid slipping during the manipulation of objects [4]. Based on the experimentally obtained result, Gunji et al. developed a robotic hand with tactile sensors that can grip unknown various weighted objects [3]. However, physiological studies have presented technical and ethical difficulties related to measuring a whole hand's manipulation because they are based on invasive measurements.

Recently, development of data gloves and systems has enabled us to measure the whole hand. Using a data glove with 15 tactile sensors, tactile patterns during a grasp and place task are categorized to seven pre-defined grasping templates [2]. In addition, using five tactile groups, a transition of 32 pre-defined grasping patterns is categorized to six manipulation templates [5]. However, analyses characterizing manipulations using data gloves with more tactile points can improve the range of observations.

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(a) Tactile sensor glove (b) Motion capture system

Fig. 1 . Appearance of tactile data glove and hand motion capture system.

Researchers who have investigated human motion and robot control have specifically examined spatial and temporal variance of state-space. Uncontrolled manifold analysis can select coordinating variables in human motion based on spatial variance over trials [8]. Moreover, when humans and robots perform dynamic whole-body actions (role-and-rise task, for example), state-space with small variance sparsely located along the time axis is known to be a critical condition for a control to succeed [7]. However, human hands have not been analyzed from the perspective of variance of state-space.

II. Materials and Methods

A. *Tactile-Motion Sensing Glove*

We used a tactile-motion data glove with a hand motion capture system and physiologically sound dense tactile data glove [9]. The hand motion capture system is implemented with inertia sensors on the back of the hand in order not to inhibit human manipulation (Fig. 1(b)). The hand motion capture system has 18 inertia sensors (222 fps). The tactile data glove has spatial and temporal resolutions designed to be comparable to those of a human hand (Fig. 1(a)). The spatial resolution is based on two-point discrimination of the human hand [10]. The glove has approximately 1000 pressure sensors, the number of which depends on the size of the subject's hand, at 1000 fps. This glove also minimizes inhibition by being thin.

B. *Precise Tactile Points and Motions*

We extracted PTPs and PMs by high repeatability and low time variance over trials (Fig. 2). The procedure used to extract PTPs and PMs is the following: (1) We segmented raw time-series to trials by a tactile event, e.g., initial contact between a

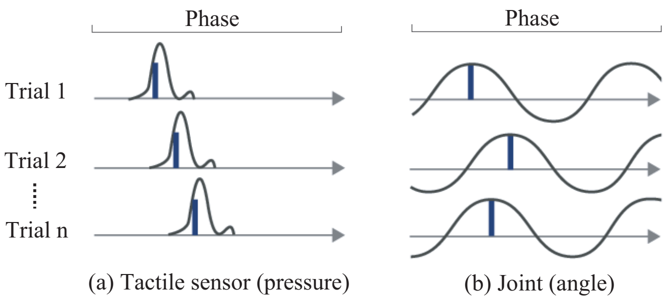


Fig. 2 . Precise tactile point (PTP) and precise motion (PM): (a) Tactile point at which it gets active with high repeatability and for which the variance of active timing is low. (b) Precise motor such that it extends or bends with high repeatability and for which the variance of motion timing is low.

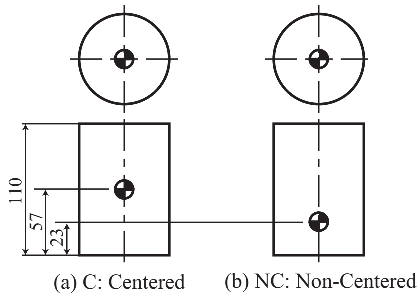


Fig. 3 . Manipulated cylinders.

Table I
SPECIFICATIONS OF THE CYLINDERS.

	Manipulation C	Manipulation NC
Weight	455 g	322 g
Height	110 mm	110 mm
Height of center of gravity	57 mm	23 mm
Diameter	72 mm	72 mm

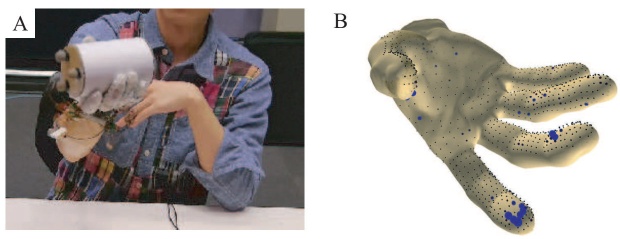


Fig. 4 . Overview of in-hand manipulation measurement. (A) Overview of experiment. (B) Reconstructed hand state using tactile data glove and motion capture system.

thumb and a manipulating object. (2) We linearly normalized the length of time duration of trials to *phase* in $[0,1]$. (3) We extracted the tactile point activated for the first time and its timing for each manipulation segment. Similarly, we extracted motions defined as extension and bending for the first time and its timing for each segment. We ignored the motion if a motion has two or more extensions and bendings. (4) We extracted them as PTPs if the tactile point which activates more than preset threshold (90%, here) of all trials and the standard deviation of the timing is less than preset threshold (0.15, here). Similarly, if the motions which always extend or bend and the standard deviation of the timing are less than a preset threshold (0.15, here), we extracted them as PMs.

To investigate the spatial distribution of PTPs, we visualized PTPs by plotting on a 3D hand model, which was scanned by a 3D scanner.

To examine the temporal distribution of PTPs, we used *mean active rate* as the index to represent the instantaneous number of active PTPs. The mean active rate is defined as the mean of the count of active PTPs in an interval of preset duration T (0.09, here). The temporal distribution of PTPs was calculated using the average over trials of mean active rate of PTPs for all phases. To investigate which PTPs were extracted in a specific time section, we visualized the repeatability of PTPs activated in the section by plotting on a 3D hand model.

III. MANIPULATION EXPERIMENT

A. Experimental Setup

We conducted a single-subject experiment to measure and analyze in-hand manipulation, rotating in-hand manipulation. The subject performed two rotating manipulations of cylindrical objects with the center of mass coinciding with the geometrical center (manipulation C) and a biased one (manipulation NC) wearing the data glove (Fig. 3, Table I). The subject was told merely to rotate the object on the table in one direction with no instruction of rotating velocity and regrasping procedure. To record natural manipulations, the subject was not told which of the two (C/NC) he was holding. The subject repeatedly rotated the cylinder 17 times in manipulation C and 26 times in manipulation NC. This experiment was conducted under ethical approval and with the informed consent of the subject.

B. Identical Regrasping Procedure in In-hand Manipulation

We observed the identical regrasping procedure in both manipulation C and NC (Fig. 5). Observed regrasping procedure is the following:

A. Put the index finger and the fingers from middle to little on the object
B. Put the index finger to the object immediately after rotating the object
C. Release and stretch the fingers from middle to little.
D. Regrasp the object with all fingers
E. Bend a thumb and put it to the object

C. Result

We characterized manipulations C and NC respectively, particularly addressing the numbers, spatial distributions and temporal distributions of PTPs and PMs. First, the number of PTPs was 99 in manipulation C and 186 in manipulation NC. Similarly, the number of PMs was 2 in manipulation C and 12 in manipulation NC (Fig. 10B, Fig. 7). This shows that the in-hand manipulations were characterized not by all tactile points and motions but by partial ones, PTPs and

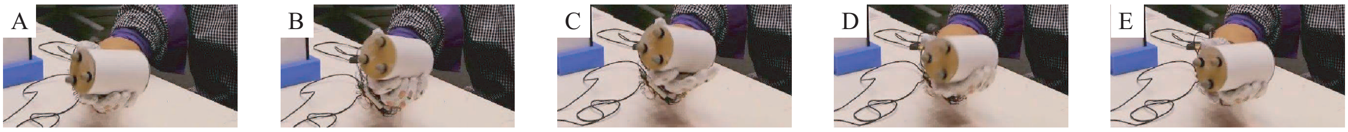
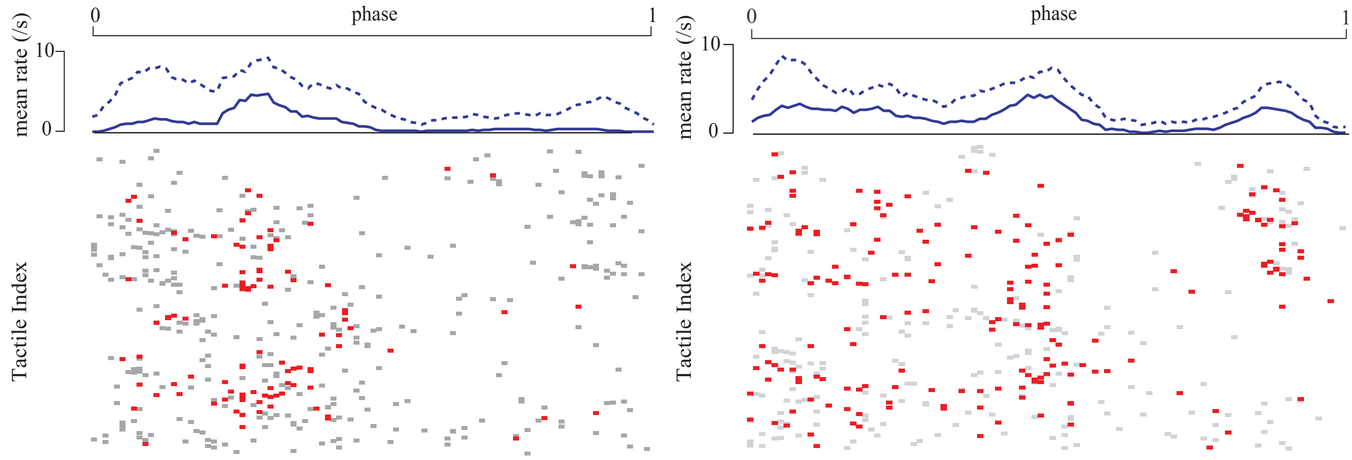


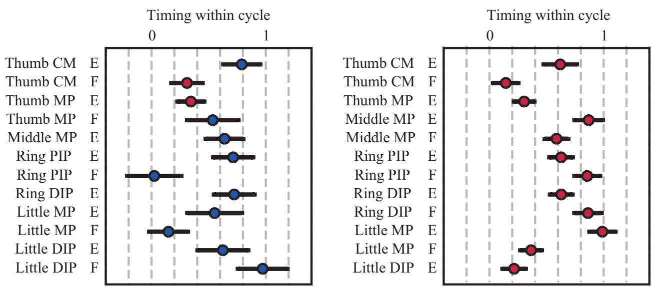
Fig. 5 . Snapshots of rotating manipulation. Images of A–E represent the corresponding regrasping procedure.



(a) Extracted tactile sensor and joint from manipulation C.

(b) Extracted tactile sensor and joint from manipulation NC.

Fig. 6 . Representative raster plots and mean active rate of PTP and non-PTPs from manipulations C and NC. Red points denote PTPs. Gray points denote non-PTPs. Blue solid line represents mean active rate of PTPs. Blue dashed line represents the mean active rate of all tactile points.



(a) Extracted joint from manipulation C.

(b) Extracted joint from manipulation NC.

Fig. 7 . Temporal distribution of PMs from manipulations of C and NC.

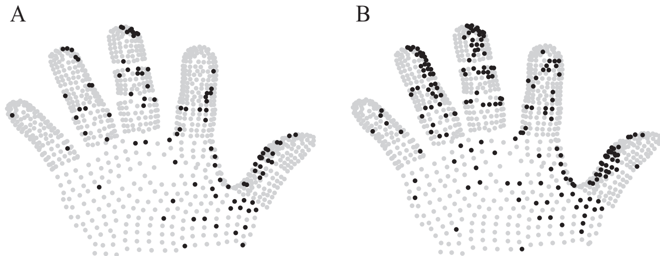


Fig. 8 . Spatial distribution of PTPs from manipulations C and NC: (A) Spatial distribution of manipulation C. (B) Spatial distribution of manipulation NC.

PMs. Second, both PTPs from manipulation C and NC were localized from the thumb to the ring finger and from the palm near a thumb (Fig. 8). Moreover, The PMs from manipulation C were localized in motions of a thumb (Fig. 7(a)). The PMs from manipulation NC were also localized in motions of the fingers except for the index finger (Fig. 7). Therefore spatial distributions of PTPs and PMs were found to be localized. Third, the representative segment shows that the PTPs from manipulation NC are localized in three time sections and the PTPs from manipulation C are localized in two time sections (Fig. 6). In addition, the PMs from manipulation C and NC were localized along the time-axis (Fig. 7). We therefore found that the temporal distribution of PTPs and PMs were localized.

To elucidate the differences of PTPs and PMs between manipulation C and NC, we compared manipulation C and NC, particularly addressing the share of spatial distributions and temporal distributions. First, the PTPs extracted from manipulation C shared 70% (69 points) of these from manipulation NC (Fig. 10B). The number of the PTPs only from NC was 117 points (11.5% of the total) (Fig. **??**(B)). In addition, all the PMs from manipulation C were extracted from manipulation NC (Fig. 7), which suggests that there are common and task-specific PTPs and PMs. Second, three sections defined by local minima of all tactile points were found (Fig. 9). In the third section, the PTPs were found only from manipulation NC (see blue sections in Fig. 9AB). Therefore the temporal differences of PTPs were localized in a specific section. Third, visualizing the spatial distribution of the PTPs in each section, we found two spatial differences: On the one hand, PTPs in the middle finger and ring finger differed in the third section (Fig. 9EH). On the other hand,

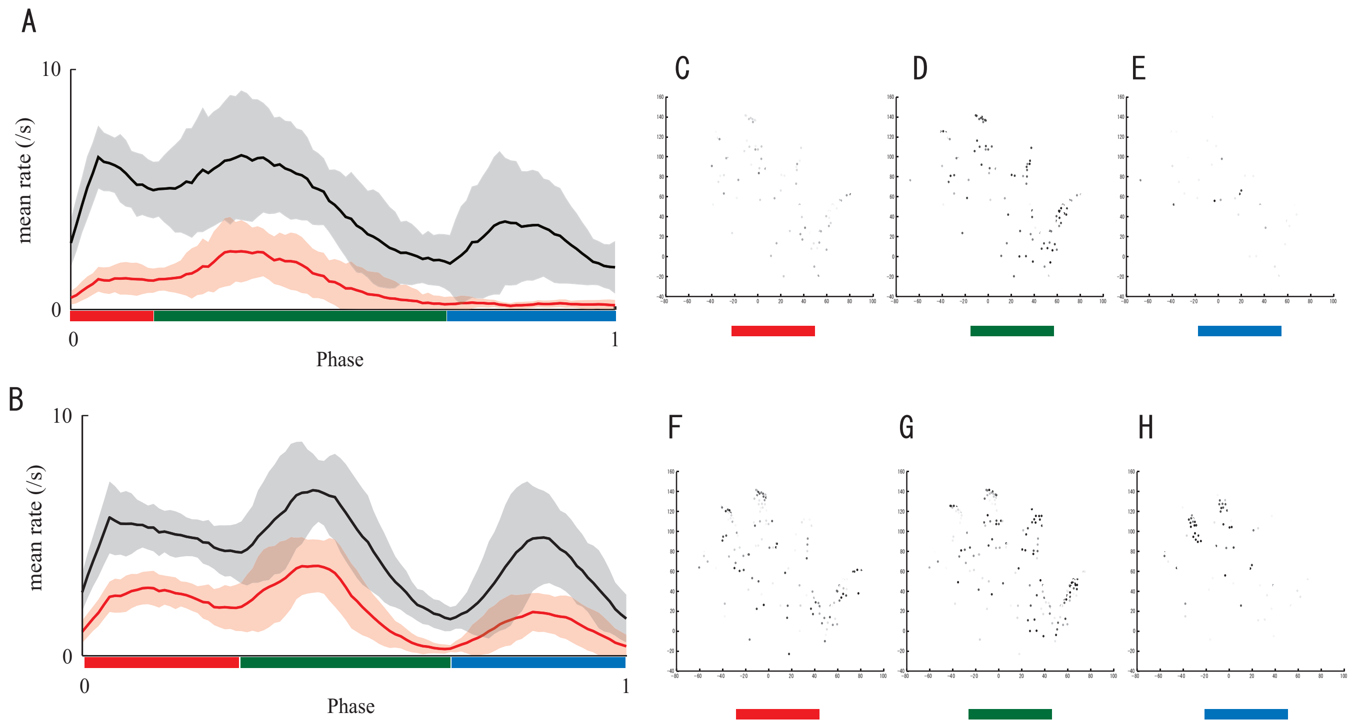


Fig. 9 . Spatiotemporal distribution of PTPs at each section. (A and B) The average over trials of the mean active rate of the tactile points in manipulation C and NC. The red solid line and envelope show the average and variance of the mean active rate of PTPs over trials. The black solid line and envelope show the average and variance of the mean active rate of all tactile points over trials. (C–E) Spatial distribution of PTPs extracted from manipulation C at each section. (F–H) Spatial distribution of PTPs extracted from manipulation NC at each section.

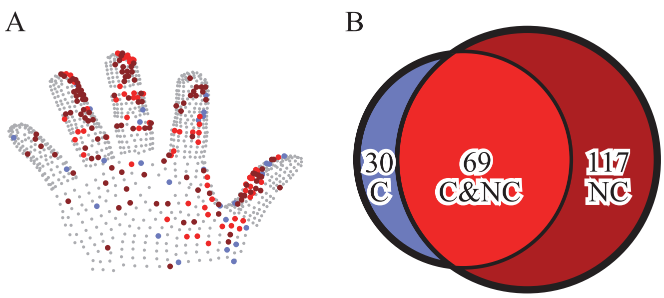


Fig. 10 . Share relation between PTPs in manipulation C and manipulation NC. (A) Spatial distribution of PTPs in manipulation C and NC. Light red points represent PTPs in manipulations both C and NC, blue points only from manipulation C, and dark red from only from manipulation NC. (B) A Venn diagram of PTPs from manipulations C and NC.

PTPs in the pulp of the index finger differed in the second section (Fig. 9DG). Thus, we found spatiotemporally localized specific differences of PTPs and PMs.

IV. Conclusion and Discussion

The precise tactile points (PTPs) and precise motions (PMs) from a rotating cylinder manipulation were extracted using a data glove with high spatiotemporal resolution and analyses to select tactile-motion variables, particularly addressing precision. The PTPs were selected such that tactile points were active with high repeatability over trials. Their active timings have low variance. In addition, the PMs are selected such that motions appear with high repeatability over trials and their timings have low variance. Results show that PTPs and PMs are localized both spatially in the hand and temporally in the task. Moreover, we compared patterns of PTPs and PMs extracted by two manipulations of cylinders with different centers of mass, using identical regrasping procedures. We therefore suggest that patterns of PTPs and PMs characterize the precise difference of manipulations that are not distinguishable using earlier analytical methods.

Although control for dextrous manipulation with a robot hand persists as an important open problem [1], no realistic controller has been developed. However, dynamic whole-body actions including complex contacts with the ground, for example roll-and-rise tasks, are known to have a ”knack,” an extremely narrow region in state-space to succeed [7]. The knacks are extracted by measuring human roll-and-rise tasks based on the convergence of the variance of motion trajectories. Emphasizing the knacks extracted from human measurement, an actual adult-size humanoid robot performs roll-and-rise motion [6]. Similar to dynamic whole-body actions, we infer that PTPs and PMs extracted from human in-hand manipulation enable control of robotic in-hand manipulation.

We show that human hands adapt to more difficult manipulation by adding PTP patterns. Manipulation NC is more difficult than manipulation C because the center of gravity of the cylinder used in manipulation NC is closer to the edge of the supporting hand polygon than manipulation C. Focusing on the difference of PTP patterns, additional spatiotemporal patterns are extracted only from manipulation NC. This result implies that more difficult tasks necessitate the use of additional TPT patterns to stabilize the manipulation.

In future work, we will conduct experiments to extract precise tactile-motion patterns from other in-hand manipulations. Over the longer term, we plan to construct a robot controller using precise tactile-motor patterns extracted from human in-hand manipulation.

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