Precise Spatiotemporal Tactile-Motor Patterns in Dexterous Manipulation Extracted using Sensing Glove

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***Abstract*—To construct robot hands for dexterous manipulation, what and when tactile points and motors are precisely used is important. Physiological studies have revealed such a detailed coordination between motors on the fingers for precision grip and tactile information. Recently, development of sensing glove allows us to extend the measuring area from fingertips to entire hand and investigate more dynamic hand manipulation. However, analysis on dexterous manipulation using whole hand only reached to static recognition and no analysis can handle precision of tactile-motor control. Here, we proposed a method to extract such a precise tactile-motor patterns localized spatiotemporally in human dexterous manipulation using a tactile-motor sensing glove with high spatiotemporal resolutions. As a result, we extracted precise tactile-motor patterns spatiotemprally located in human hand manipulation, which cannot be distinguished by prior methods. Moreover, we preliminarily suggest that when difficulty of manipulations increases humans add such new tactile-patterns to human hand controller to stabilize manipulations.**

I. Introduction

One characteristic of human dexterous manipulation compared to robotic one is the ability to manipulate objects dynamically. To construct robot hands for dexterous manipulation, what and when tactile points and motors are precisely used is important.

Physiological studies using invasive measurement of the fingers used in precision grips have revealed coordination between precision grips and tactile information. For example, when slippage of object is detected, fingers increase grip force to prevent slippage after approximately 100 ms [4]. Since such feedback is enough to implement to robotics, robots with human-like gripping force adjustment have been developed [3].

Recently, development of sensing system allows us to extend the measuring area from fingertips to whole hand and investigate dynamic dexterous manipulation [2]. Using such a sensing glove, Faria et al. have clusterized tactile input in dexterous manipulation [2]. Kondo et al. have recognized contact state in dexterous manipulation and controlled robot hand using its transition [5].

However, no study have investigated crucial tactile points and motors although previous study have measured and analysed human dexterous manipulation. We consider there are following 2 problems within prior studies: First, the resolutions of sensing systems and analysises was not enough to capture human tactile-motor dynamics. Second, the analysis was static to characterize dynamic human dexterous manipulation because prior analysis dismissed a tactile-motor structre over repeated trials.

Here, we proposed a method to extract such precise tactile-motor patterns that can characterize dynamics in human dexterous manipulation using a tactile-motor sensing glove with high spatiotemporal resolutions. First, we constructed a sensing glove with high spatiotemporal resolutions comparable to human hand [6]. Second, we extracted tactile-motor patterns where human manipulate precisely using spatiotemporal variances over trials: repeatability and small time variance.

As a result, we extracted precise tactile-motor patterns spatiotemprally located in human hand manipulation, which cannot be distinguished by prior methods. We found difference of such patterns even when dexterous manipulations are conduted in the identical regrasping procedures. Prior analysis on human dexterous manipulation cannot distinguish such precision because they regard manipulations as the same when regrasping patterns are the same.

Moreover, our results preliminarily suggest that when difficulty of manipulations increases humans add such new tactile-patterns to human hand controller to stabilize manipulations. We believe that such patterns, which are a constraint of human manipulation using data glove, can be a useful guideline to design remarkablly dexterous robot hands.

The reminder of this paper is organized as follows: in the next section, we present related background on measurement of human hand including physiological studies and ones using whole-hand sensing gloves. Section III describes our first contribution: a method to extract precise control in human dexterous manipulation. Section IV then details our second contribution: spatiotemporally localized ”common” and ”additional” controls. Finally, we conclude with a summery of our findings and discussion of future work in Section V.

II. Materials and Methods

It is important for a robot designer to know which tactile points and motors plays crucial role to a dexterous manipulation. One of the ways to extract such tactile points and motors is to measure human dexterous manipulation and analyze its structures.

In order to record natural human dexterous manipulation, we require sensing glove with 3 following features: able to measure tactile points and motors simultaneously, thin enough not to inhibit human manipulation and enough to copy human tactile inputs.

We hypothesized such tactile points and motors that activates with both spatial and temporal precision because they can be a strong constraint of dexterous manipulation. We

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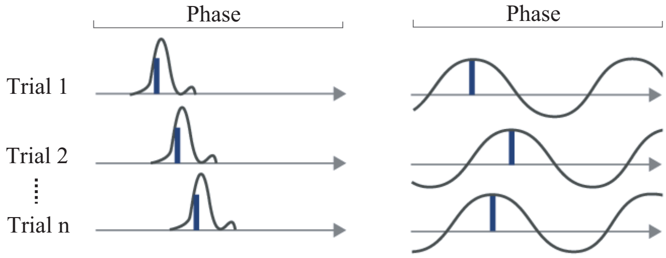
(a) Tactile sensor glove (b) Motion capture system

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



(a) Tactile sensor (pressure) (b) Joint (angle)

Fig. 2 . Tactile points and motors which are extracted and not extracted.

considered there are two precision, spatial one and temporal one. First, spatial precision which is defined by repeatability of activation gives us a constraint on what tactile points and motors should be used constantly in a specific dexterous manipulation. Second, temporal precision indicating a variance of activated timing presents a constraint on when tactile points and motors should activate.

Using the indicators, repeatability and time variance, we analysed three structures of manipulations: the identical regrasping procedure, spatial distribution of precise tactile points and motors and temporal distribution of them. Regrasping procedure is defined as sequence of movements of fingers. We predicted that precision of tactile points and motors in manipulations were different even when the manipulations had the identical regrasping procedure. In order to make sure the difference among patterns of precise tactile points and motors was derived not by different regrasping procedure but by tactile-motor dynamics. Note that previous research based on clusterizing and grasp taxonomy can not discriminate these two manipulation.

A. Tactile-Motor Sensing Glove

We employed tactile-motor sensing glove which has hand motion capture system and physiologically sound dense tactile sensing glove [6]. 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)). Hand motion capture system has 18 inertia sensors (222 fps). Tactile sensing glove has spatial and temporal resolutions comparative to be comparable to human hand (Fig. 1(a)). The spatial resolution is based on physiological evidence, two-point discrimination of the hand [7]. The glove has approximately 1000 pressure sensors, the number of which depends on size of subject's hand, at 1000 fps. This glove also minimize the inhibitation by being made thin.

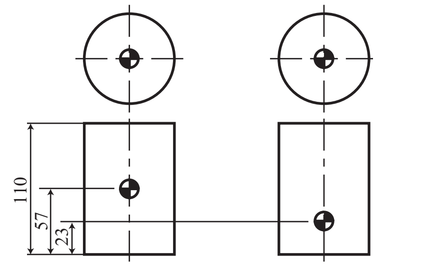
B. Precise Tactile Points and Motors

We extracted precise tactile points and motors by high repeatability and low time variance over trials (Fig. 2). The procedure to extract precise tactile points and motors is as follows: (1) First, we segmented tactile-motion time series of manipulation by tactile event, e.g., initial contact between first finger and a manipulating object. (2) Second, we normalized length of segmented time series to phase in the section from 0 to 1 in order to make comparable over trials. (3) Third, we extracted active tactile points and motors and its timing for each manipulation segment. We regarded tactile point with certain pressure in the segment as active tactile point. Timing of active tactle point is defined as the first contact timing of the tactile point in the segment. Also, we extracted an active motors with only one extreme of the angle. We dismissed motors with two of more extremes. Timing of active motor is defined as the timing of the extreme. (4) Finally, we extracted precise tactile points and motors from active ones when repeatability was higher and time variance was lower than a certain threshold. For each tactile point or motor, repeatability was calculated by ratio of trials in which it was active. Likewise, time variance was calculated by variance of timing of active tactile points and motors. We set repeatability threshold as 90% and time variance threshold as 0.15 in normalized segment arbitararily.

In order to investigate spatial tactile distribution, we visualized precise tactile points by plotting it on a 3D model of the hand, which was scanned by 3D scanner. We compared the distribution of precise tactile points and motors by counting the shared and not-shared number of them. Also, to compare the distribution of precise motors, we counted the number of shared number of them.

We employed "mean active rate" as the index to indicate the instantaneous number of active precise tactile points for temporal distribution of precise tactile points. Mean active rate is defined as the count of active precise tactile points in an interval of duration T divided by T. We set T 9% of the total length of normalized segmented time series.

We investigated what and in what section in manipulation the precise tactile points and motors increase. We defined section of manipulation by local minimums of the average of mean active rate of all tactile points over trials because such timing indicates the beginning of touch. To calculate temporal distribution of precise tactile points of manipulation, we computed the average of mean active rate over trials at each phase. Moreover, we observed spatial distribution of precise tactile points in a specific section by visualizing repeatability of the precise tactile points only in each section on a 3D model of the hand.



(a) C: Centered (b) NC: Non-Centered

Fig. 3 . Manipulated cylinders.

Table I
SPECIFICATION OF THE CYLINDERS.

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

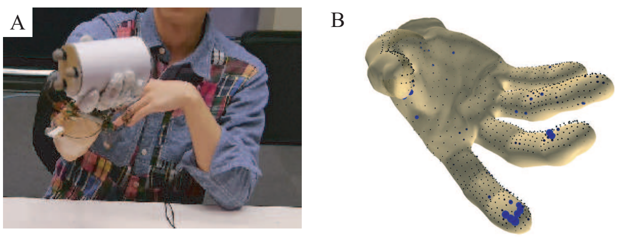


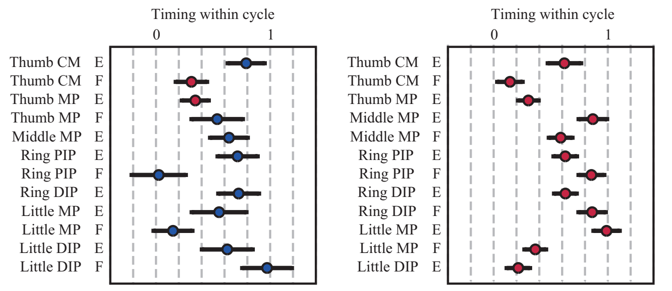
Fig. 4 . Overview of in-hand manipulation measurement. (A) Overview of experiment. (B) Reconstructed hand state using tactile sensing glove and motion capture system.

III. MANIPULATION EXPERIMENT

A. Experimental Setup

We conducted a single-subject experiment to measure and analyse dexterous manipulation. We employed rotating dexterous manipulation as a example of human dexterous manipulation. The rotating manipulation is a task in which a subject are required to rotate a cylinder object in one direction using whole hand. Also, it is difficult to know the crucial tactile points and motors beforehand because this task includes regrasping procedure. This experiment is conducted under ethical approval and informed consent of the subject.

In this work, the subject performed rotating manipulations of cylinder objects with centered CoP (manipulation C) and non-centered CoP (manipulation NC) using the data glove (Fig. 3, Table I). The subject was told to just rotate the object on the table in one direction without any instruction of rotating velocity and regrasping procedure. We counted his rotation and instructed to stop when he rotated 18 times. To record natural manipulations, the subject was blind to what object he would manipulate. We dismissed the recorded data of rotations at the beginning of the three times to focus on analyzing stable manipulations.



(a) Extracted joint from manipulation C. (b) Extracted joint from manipulation NC.

Fig. 7 . Temporal distribution of precise motors from manipulations of C and NC.

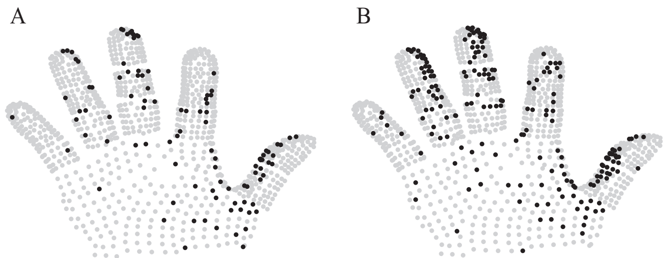


Fig. 8 . Spatial distribution of precise tactile points from manipulations C and NC. (A) Spatial distribution of manipulation C. (B) Spatial distribution of manipulation NC.

B. Identical Finger-Gaiting in Dexterous Manipulation

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

A. Put the first finger and the fingers from third to fifth on the object
B. Put the second finger to the object immediatele after rotating the object
C. Release and stretch the fingers from third to fifth.
D. Regrasp the object with all fingers
E. Bend the first finger and put it to the object

C. Result

To characterize precision of manipulation, we counted the number of precise tactile points and motors. In this experiment, the number of precise tactile points was 99 in manipulation C and 186 in manipulation NC. Similarly, the number of precise motors was 2 in manipulation C and 12 in manipulation NC (Fig. 9B, Fig. 7).

We observed that distribution of precise tactile points and motors was spatially localized. The precise tactile points are localized in the fingers from first to fourth and palm near the palm (Fig. 8). The precise motors are also localized at motors on the first finger in manipulation C and on the fingers except for second finger is manipulation NC (Fig. 7).

We also observed that distribution of precise tactile points and motors was temporally localized. We found that the precise tactile points are localized in 3 time intervals in a segment of manipulation NC and 2 time intervals in one of

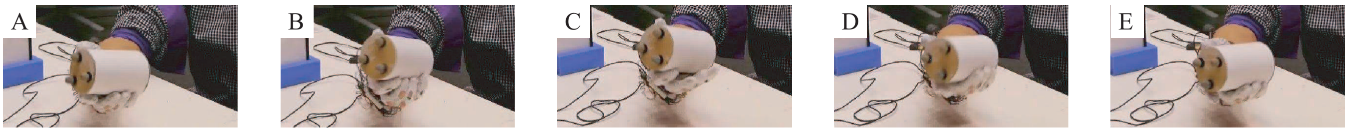
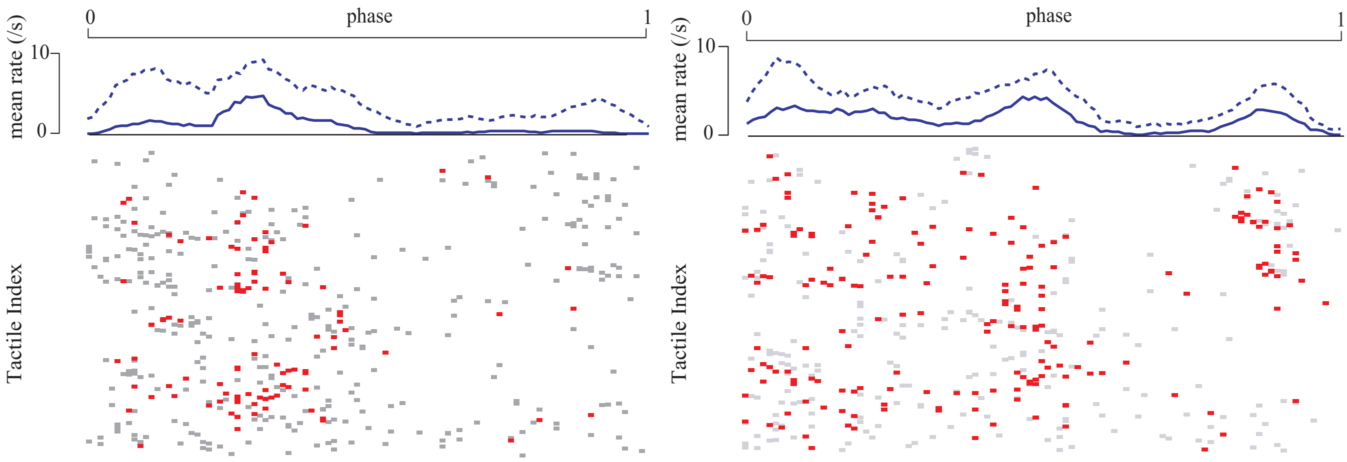


Fig. 5 . Snapshots of rotating manipulation. The pictures of A-E represent the corresponding regrasping procedure.



(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 precise and non-precise tactile points from manipulation C and NC. Red points indicate precise tactile points. Gray points indicate non-precise tactile points. Blue solid line represents mean active rate of precise tactile points. Blue dashed line represents mean active rate of all tactile points.

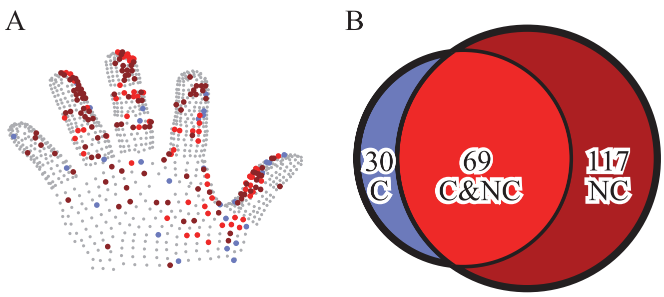


Fig. 9 . Relationship between precise and motors of manipulation C and manipulation NC. (A) Spatial distribution of precise tactile points from manipulation C and NC. Light red points represent precise tactile points from manipulations both C and NC, blue points from only from manipulation C, dark red from only from manipulation NC. (B) A Venn diagram of precise tactile points from manipulations C and NC.

manipulation C, which lacks for the precise tactile points in the latter half time interval compared to manipulation NC.

To capture the spatial relationship, we analysed share of the precise tactile points and motors between manipulation C and NC. The precise tactile points extracted from manipulation C shared 70% (69 points) of these from manipulation NC (Fig. 9B). The number of the precise tactile points only from NC is 117 points, which is 11.5% of the total. Also, all the precise motors from manipulation C are extracted from manipulation NC.

Compareing the averages of mean active rate over trials, we investigated when the precise tactile points and motors increase. We found there was three sections defined by local minimum of the non-precise tactile points. Moreover, the precise tactile points from manipulation NC was found in the third section althogh these from manipulation C was not found (see blue sections in Fig. 10AB).

We conducted datailed analysis on spatial distribution of the precise tactile points in each section. As a result, we found two spatial difference: First, the difference in the third section is derived by tactile points in the third finger and fourth finger (Fig. 10EH). Second, the difference in the second section mainly arise from tactile points in the pulp of the second finger(Fig. 10DG).

IV. Discussion

What and when tactile points and motors are precisely used in human dexterous manipulations is important for understanding of manipulations and robot design. In this work, we proposed a method to extract such a precise tactile-motor patterns localized spatiotemporally in human dexterous manipulation using a tactile-motor sensing glove with high spatiotemporal resolutions.

We extracted the difference between precise tactile-motor patterns from manipulations with identical regrasping procedures. This suggests that humans adjust tactile-motor control by adding or trimming such patterns depending on manipulating objects.

Although control for dextrous manipulation with robot hand is an important open problem, its uniform way is not

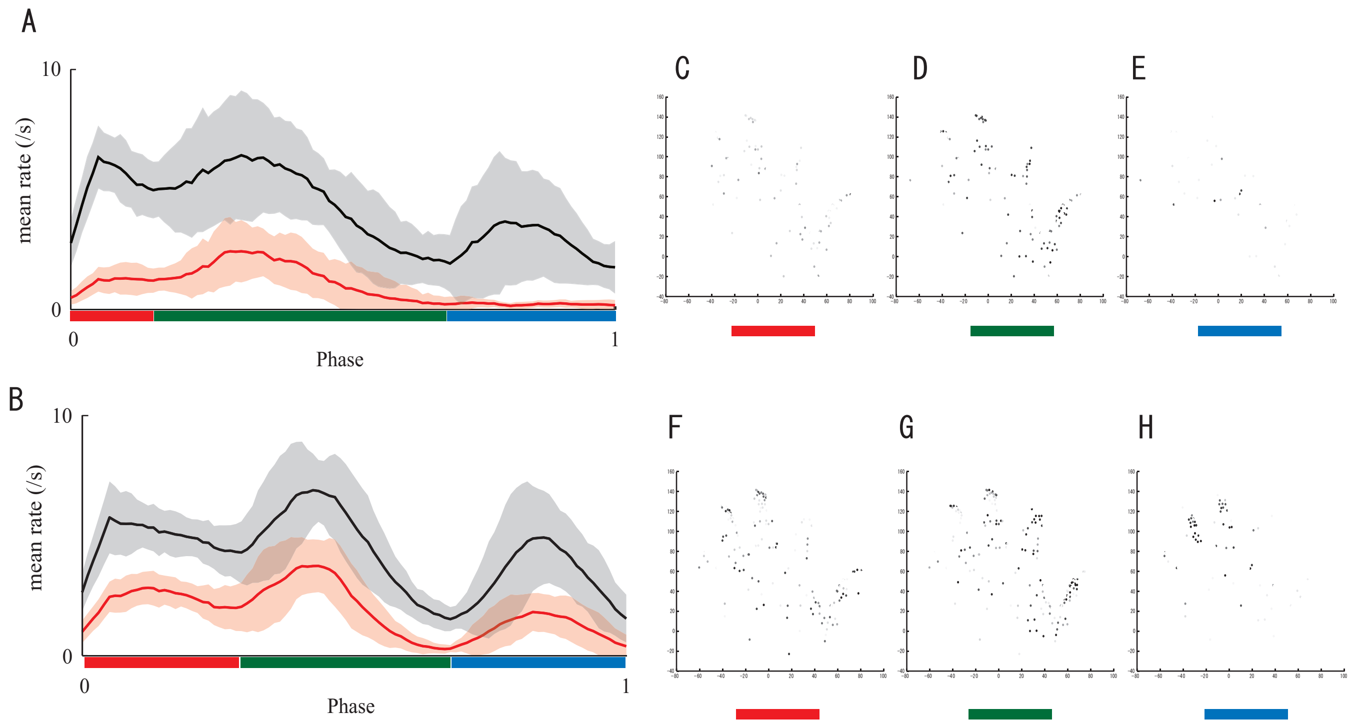


Fig. 10 . Spatio-temporal distribution of precise tactile points at each section. (A and B) The average over trials of the mean active rate of the tactile points in manipulation C and NC. Red solid line and envelop indicate the average and variance of the mean active rate of precise tactile points over trials. Black solid line and envelop indicate the average and variance of the mean active rate of all tactile points over trials. (C-E) Spatial distribution of precise tactile points extracted from manipulation C at each section. (F-H) Spatial distribution of precise tactile points extracted from manipulation NC at each section.

established [1]. Using our proposed method, we specifically presented whan and what tactile points and motor is precisely manipulated by human dexterous manipulation. Our result contribute to robotics in the way this may enable robot designers to give a constraint of spatiotemporal tactile-motor state of controller for dexterous manipulation.

The difference of spatiotemporal tactile-motor patterns can be derived by the difficulty of the tasks. The CoP of the cylinder used in manipulation NC is closer to the edge of supprting hand polygon than manipulation C. This means manipulation NC is more difficult to stable than manipulation C. The addition of the tactile-motor patterns can be explain in the way that manipulation NC requires more tactile-motor controls to stabilize the manipulation.

In future work, we will conduct covering experiment in order to extract precise tactile-motor patterns from specific dexterous manipulations. We believe that such patterns, which are a constraint of human manipulation using data glove, can be a useful guideline to design remarkablly dexterous robot hands.

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