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

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***Abstract*—Physiological studies about hand manipulation have revealed coordination between precision grips 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, its analysis only reaches to static recognition and there have not been fundamental tactile-motor characterization over repeated trials. Here, we introduce fundamental indice over trials focusing on precision of control to assess importance of tactile points and motors to realize dexterous manipulation. We measured rotating cylinder manipulation using sensing glove with high spatio-temporal resolutions and applied the precision indice. As a result, we find that such precise tactile-motor patterns are localized in phase of each task. Moreover, we suggest that when task difficulty increases human adds new patterns to those at an easy task.**

I. Introduction

One characteristic of human dexterous manipulation other than robotic one is the ability to manipulate objects dynamically. The capability can be exhibited by the coupling between highly rapid and precise motors and distributed tactile sensors in human hands. We believe that discovering such coupling contribute to robotic hands acting dynamic dexterous manipulation.

In this work, we extracted spatio-temporal tactile-motor patterns assumed to be used for precise control in human dexterous manipulation. We hypothesized that human hands precisely manipulate neither anytime nor anywhere but spatio-temporally localized. Extracting such localized control enables robots to perform roughly in easy domain and severely in hard one.

Our first contribution is a method to extract spatio-temporal tactile points and motors characterizing precise control in human dexterous manipulation. We achieved this by introducing indice based on repeatability and small time variance, which characterize precision. In comparison to existing methodology for dexterous manipulation, such as clustering or gaussian process, our method can explicitly deal with variance in timing of touch which appears to be important for dexterous manipulation. Moreover, this enables us to examine precision of tactile inputs and motors at the same index.

Our second contribution is, using the method and a sensing glove with high spatio-temproal resolutions, a novel discovery that human dexterous manipulation has spatio-temporally localized controls. Experiments using sensing glove with high spatio-temproal resolutions suggest that there are "common" control and "additional" control at dexterous manipulation with the same regrasping procedure; precise tactile-motor pattern of one manipulation can be explained by adding optional pattern to common pattern.

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: spatio-temporally localized "common" and "additional" controls. Finally, we conclude with a summery of our findings and discussion of future work in Section V.

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II. Background

Physiological studies using invasive measurement of fingers on hand manipulation 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 [3]. Since such feedback is enough to implement to robotics, robots with human-like gripping force adjustment have been developed [2].

Recently, development of sensing glove allows us to extend the measuring area from fingertips to whole hand and investigate dynamic dexterous manipulation [5]. Using such sensing glove, Faria et al. have clusterized tactile input in dexterous manipulation [1]. Kondo et al. have recognized contact state in dexterous manipulation and controlled robot hand using its transition [4].

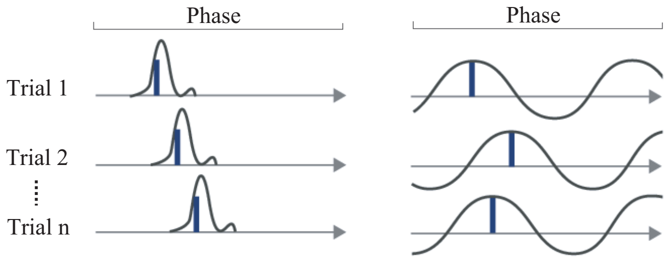
In dexterous manipulation, however, its analysis only reaches to static recognition and fundamental tactile-motor characterization over repeated trials have not been investigated. In this paper, we introduce fundamental indice over trials focusing on precision of control to assess importance of tactile points and motors to realize dexterous manipulation.

III. Extraction of Spatio-temporally Precise Tactile Points

In this section, we present the way to measure and extract precise tactile points and motors in dexterous manipulation. First we specify requirement of sensing glove and introduce our set-up. Next, we present a method to extract precise tactile points and motors in terms of repeatability and low time variance.

(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.

A. *Tactile-Motor Sensing Glove with high spatio-temporal resolution*

In order to extract spatio-temporally precise tactile points and motors in natural dexterous manipulation, sensing glove requires 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.

To meet this requirement, we employed tactile-motor sensing glove which has hand motion capture system and physiologically sound dense tactile sensing glove [5]. 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 [6]. 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*

Tactile points and motors which always get active in a human dexterous manipulation is important can give the essential state required by the task. Thus extracting precision of tactile points and motors is important theme to a robot designer.

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.

IV. Manipulation Experiment

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.

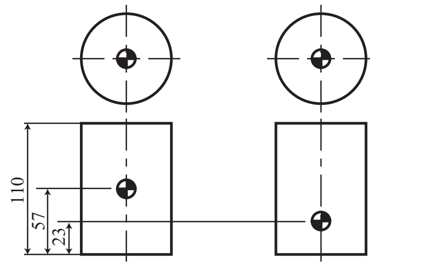
We especially focus on precision of tactile points and motors because they can be a strong constraint of a task. We considered there are two precision, spatial one and temporal one. To quantify these precision, we employed two indicators: spatial repeatablility and temporal low variance.

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 compared two manipulations which have the identical regrasping procedure because we predicted the distributions of precise tactile points and motors differ even when regrasping procedure is identical.

A. *Experiment of Dexterous Rotating Manipulation*

We employed rotating dexterous manipulation as a toy problem to measure and analyze. The rotating manipulation is a task in which a subject are required to rotate a cylinder object in one direction using whole hand. It is difficult to know the crucial tactile points and motors beforehand because this task includes regrasping procedure.

In this work, we measured rotating manipulation of cylinder objects with centered CoP (manipulation C) and non-centered CoP (manipulation NC) using the data glove (Fig. 3, Table I). The number of a subject was 1. 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



(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

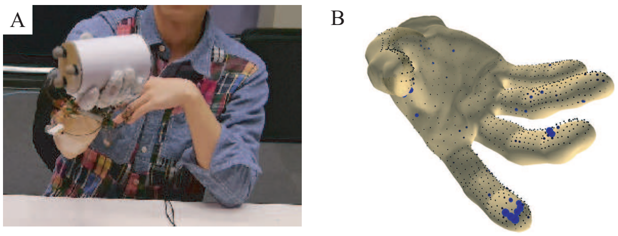


Fig. 4 . Overview of in-hand manipulation measurement. (A) Overview of experiment. (B) Reconstructed hand state using tactile sensing glove and motion capture system.

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.

B. Identical Finger-Gaiting in Dexterous Manipulation

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 sensorimotor dynamics, we checked the manipulations have the identical regrasping procedure. Note that previous research based on clusterizing and grasp taxonomy can not discriminate these two 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. Precise Tactile Points and Motors in Rotiting Manipulations

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).

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. 7). 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. 8).

We also observed that distribution of precise tactile points and motors was temporally localized. We employed 'mean active rate' as the index to indicate the instantaneous number of active 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 ($T = 0.09$). Using this index, 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 manipulation C, which lacks for the precise tactile points in the latter half time interval compared to manipulation NC.

D. Spatial Comparison

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.

E. Temporal Comparison

We investigated when the precise tactile points and motors increase. To calculate temporal distribution of precise tactile points of manipulation, we computed the average of mean active rate over trials at each phase. As a result, 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 detailly investigated spatial distribution of the precise tactile points in each section. To visualize it, we calculated repeatability 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).

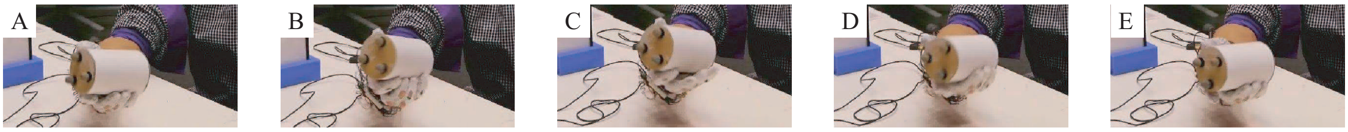
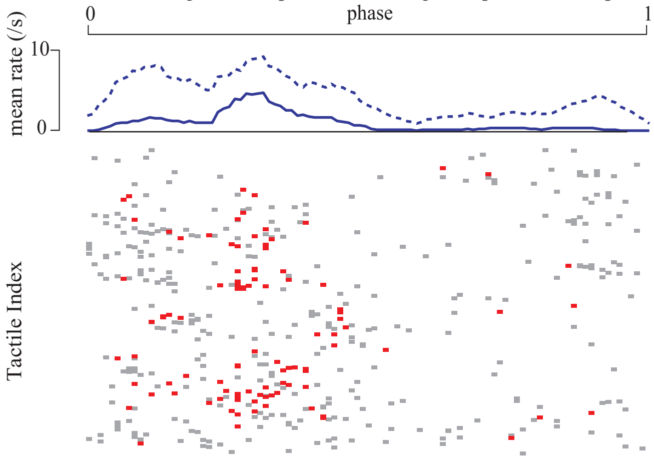
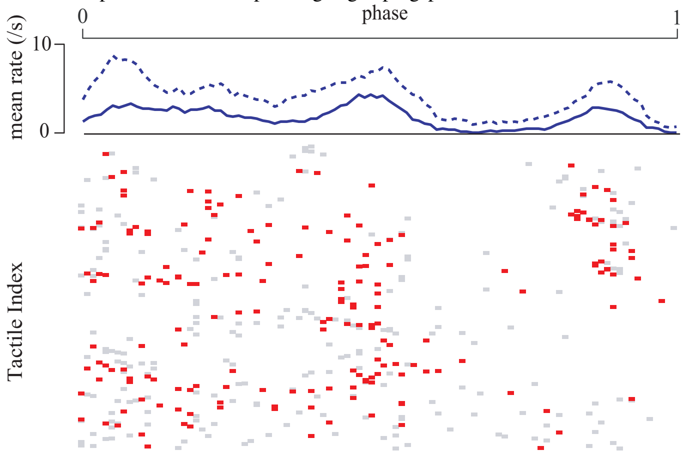


Fig. 5 . Snapshots of rotating manipulation. The pictures of A-E represent the corresponding regrasping procedure.



(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.

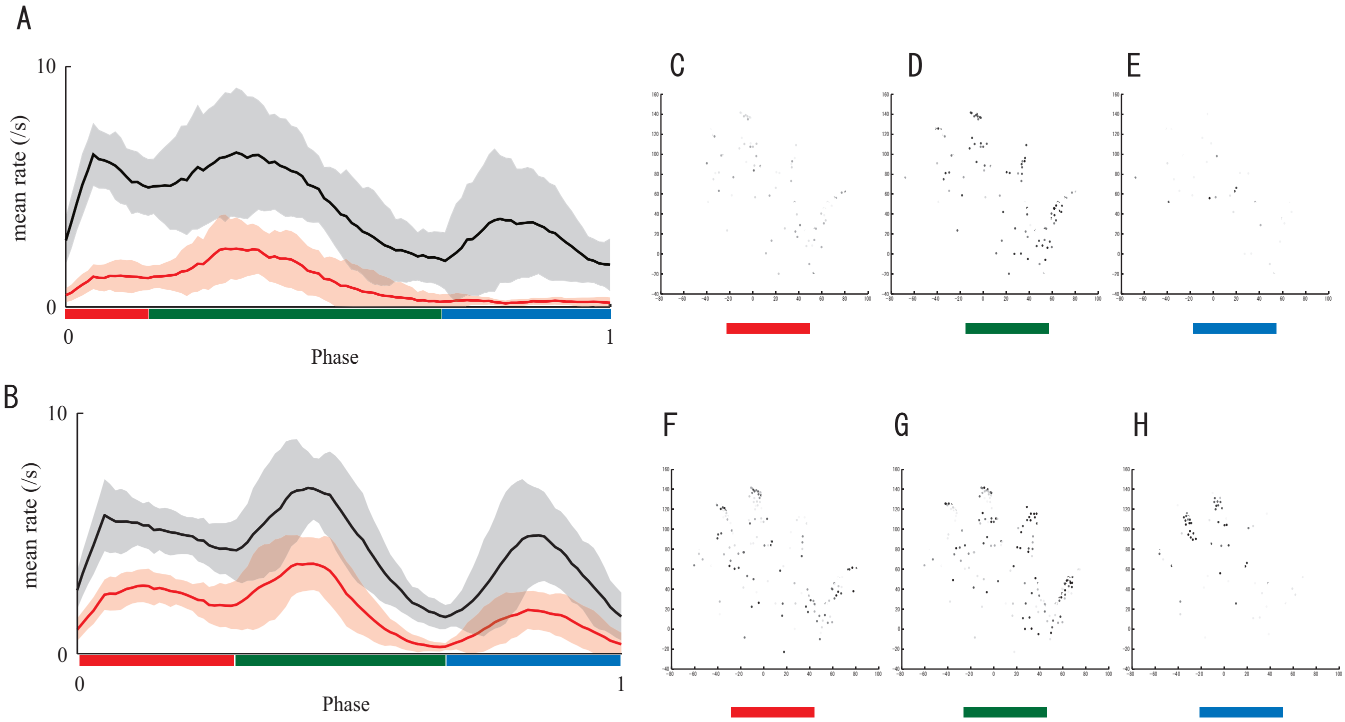


Fig. 10 . Spatio-temporal distribution of precise tactile points at each section. (A and B) The average over trials of the mean active rate of the tactile points in manipulation C and NC. Red solid line and envelop indicate the average and variance of the mean active rate of precise tactile points over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

V. Conclusions

In this work, we found that precise tactile-motor patterns are localized in phase of each task. Moreover, we suggest that when task difficulty increases human adds new patterns to

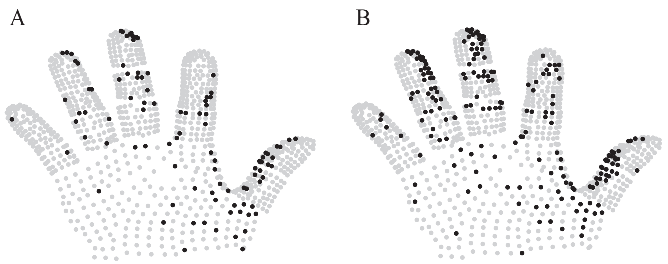
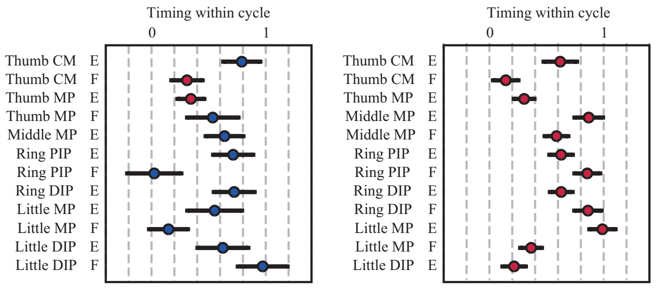


Fig. 7 . Spatial distribution of precise tactile points from manipulations C and NC. (A) Spatial distribution of manipulation C. (B) Spatial distribution of manipulation NC.



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

Fig. 8 . Temporal distribution of precise motors from manipulations of C and NC.

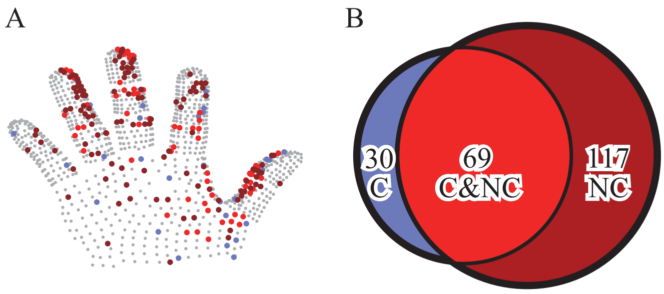


Fig. 9 . Relationship between precise and motors of manipulation C and manipulation NC. (A) Spatial distribution of precise tactile points from manipulation C and NC. Light red points represent precise tactile points from manipulations both C and NC, blue points from only from manipulation C, dark red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

those at an easy task.

まずこういう手法で，具体的な制御に落とし込めるレベルの解析が可能である．

It is important to note that difference among patterns of precise tactile points and motors was derived not by different regrasping procedure but sensorimotor dynamics. Note that previous research on these two manipulation can not be

操作 NC と操作 C の重心位置と手の位置関係から，操作の難易度を考える．操作 NC は円柱の重心が偏っており，手の上における物体の支持多角形の縁に物体の重心が近い．一方，操作 C は真ん中に重心があるため，指示多角形の中央部分に物体の重心が存在する．従って，物体が今にも手から落ちそうである操作 NC のほうが難しい物体操作であると考えられる．物体操作の難化に対応している可能性が示唆された．空間分布と時間分布を調べた結果をまとめると，人が行う物体操作の難化に対応する接触運動を，ロバストな接触運動パターンの追加によって説明できる可能性が示唆された．

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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