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# MOTOR ADPTATION TO DYNAMIC ENVIRONMENTS IN ARM REACHING MOTIONS

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**Abstract**: In daily life, humans must compensate for the resultant forces arising form interaction with the physical environment. Recent studies have shown that humans can acquire a neural representation of the relation between motor command and movement, i.e. learn an internal model of the environment dynamics. The present paper discusses whether humans can identify one side of dynamics from the mixed environment dynamics in the case where humans have experienced either of them.

**Keywords:** motor adaptation, internal model, force field, reaching motion, dynamic environment.

## 1. INTRODUCTION

To manipulate objects or to use tools, humans must compensate for the resultant forces arising form interaction with the physical environment. Recent studies have shown that humans can acquire a neural representation of the relation between motor command and movement, i.e. learn an internal model of the environment dynamics. Then, we can compensate for the mechanical perturbation in a feedforward manner.

Humans can learn an enormous number of motor behaviors in different environments. Then, it is required to construct multiple internal representations of various dynamic environments, which can be recollected corresponding to each environment. Several previous studies have examined arm movement adaptation to multiple dynamic environments [1]-[5]. The concept of multiple models implies the ability to adapt to diverse perturbations with different contexts and to make efficient use of redundancy by performing the same task in different ways under different environments [6]-[9].

Karniel et al [10] examined the hypothesis that subjects would adapt to a sequence of perturbations by employing multiple models and learn to switch between according to the sequence context. It is then concluded that the subjects try to represent the alternating perturbations with a single internal model unless the subject can predict alternating sequence of perturbations. However, it is noted that this result does not reject the explanatory capability of multiple models for many other motor behaviors.

Rao and Shadmehr [11] demonstrated context switching between perturbations after long training of one movement with spatial cues. Further, Wada et al [12] recently found that if the resistive or assistive viscous force fields were cued by a blue or red color display, humans were able to learn the multiple and distinct internal models of the two force fields and appropriately switch them even for a random presentation. This study indicates that the difficulty in learning is determined by the balance between the effectiveness of contextual information and the similarity of force fields.

Osu et al [13]demonstrated that subjects could adapt to two opposing force fields when provided with audiovisual cues before movement, which suggests that multiple internal models can be acquired simultaneously during learning and predictively switched, depending only on contextual information.

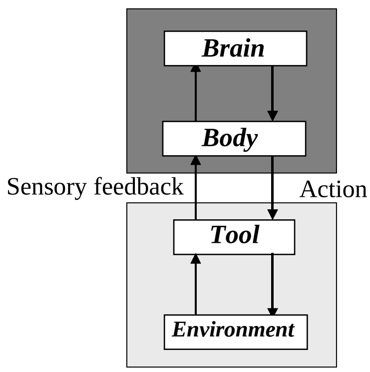



**Fig.1** Body-Tool-Environment system.

Now, we utilize many kinds of tools to achieve various tasks in daily life, which is used to supplement or expand the body kinematics or dynamics [14]. As shown in Fig.1, the tool connects the body with the environment. In order to realize the task quickly, smoothly or efficiently, it is required to adjust the kinematic and dynamic relations among the body, tool and environment according to the task.

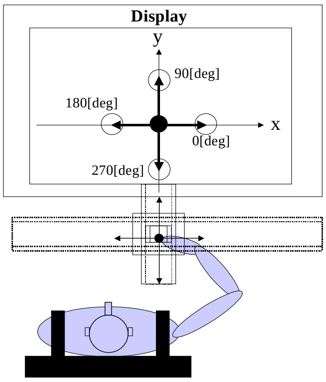



**Fig.2** Experimental set up.

Since the tool is used in different environments, we have to separate the tool dynamics from the mixed dynamics.

The present paper discusses whether humans can identify one side of dynamics from the mixed force field in the case where humans have experienced either of added force fields.

## 2. EXPERIMENTS

### *2.1. Experimental setup*

The experimental apparatus is shown in Fig.2. The manipulandum (x-y table) is actuated by a couple of linear direct drive motors (x axis: max. 599 N, y axis: 197 N; NSK Ltd), which are controlled by the digital servo at the sampling rate 2 KHz and can generate various mechanical impedances against the grip grasped by the subject. The position of motor is detected by the digital encoder (1,000,000 pulse/m, resolution: 1 μm). The reaction force of hand grip is measured by the six-axis force sensor (Nitta: IFS-67M25A-25-I40, resolution rate: 0.6 g). The hand position is displayed on the front screen by the projector.

The subject is seated on the chair with adjustable height in front of the experimental equipment and the shoulder is fixed on the back of the chair by the strap. The hand and elbow are locked up by the support rack on the same height as the shoulder.

The horizontal point-to-point arm movements are performed by the upper limb with three degrees of freedom. The subject is instructed to reach the target from the initial position with a velocity within the range of 300±100 msec. Four target positions are located at 0.1 m radius from the origin (center) in the directions of 0° , 90° , 180° , 270° . The target area is within the radius 30 mm. The initial and final hand positions are displayed on the screen, but the hand position during movement is not displayed to avoid being affected by the visual feedback.

### *2.2. Dynamic environments*

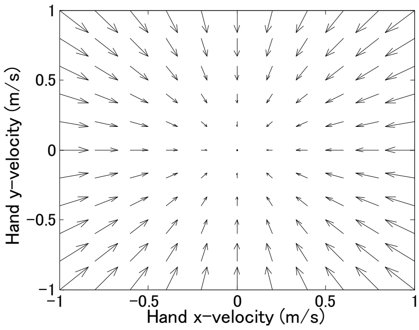
The manipulandum generated three kinds of dynamic environments V1, V2, P which were added to the grip grasped by the subject as shown in Fig.3.

V1 $$\boldsymbol{F}_{\mathrm{V1}} = \boldsymbol{B}_{\mathrm{V1}}\boldsymbol{v} = \begin{bmatrix} -b & 0 \\ 0 & -b \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} \quad [\mathrm{N}] \tag{1}$$

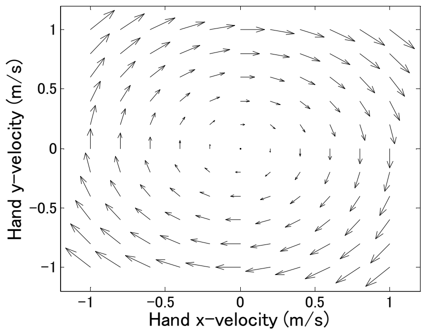
V2 $$\boldsymbol{F}_{\mathrm{V2}} = \boldsymbol{B}_{\mathrm{V2}}\boldsymbol{v} = \begin{bmatrix} 0 & b \\ -b & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} \quad [\mathrm{N}] \tag{2}$$

P $$\boldsymbol{F}_{\mathrm{P}} = \boldsymbol{K}d\boldsymbol{p} = \begin{bmatrix} 0 & -k \\ k & 0 \end{bmatrix} \begin{bmatrix} dx \\ dy \end{bmatrix} \quad [\mathrm{N}], \tag{3}$$

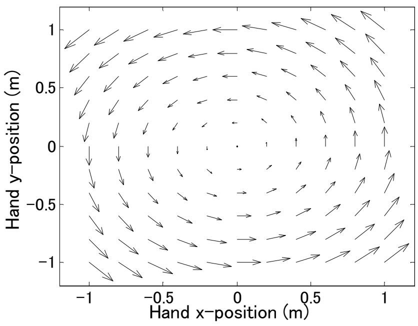
where b= 15 N/(m/s), k= 50 N/m. V1 is a resistive viscosity force field in proportion to the velocity in the direction of movement. V2 is a clockwise rotational viscosity force field in proportion to the velocity in the direction of movement. P is a counterclockwise rotational force field in proportion to the displacement in the direction of movement.




(a) Viscosity force field V1




(b) Viscosity force field V2




(c) Position dependent force field P

**Fig.3** Three kind of force fields.

*2.3. Experimental procedure*

The experimental procedure is shown in Fig.4. The difference between Experiments I and II is whether the first force field is V1 or V2.

1) First, sufficient successful trials to four directions are asked under the null field (NF) for training. NF means no force filed, i.e. free reaching motion.
2) Next, under the viscosity force field V1, 320 trials were performed for learning.
3) Then, under the compounded force field [V1+P], 320 trials were performed for learning.
4) Finally, 320 trials were performed under the force field P for learning.

Eight student males participated in the experiments. The subjects were divided into four groups. Each of four experiments was performed by two subjects.

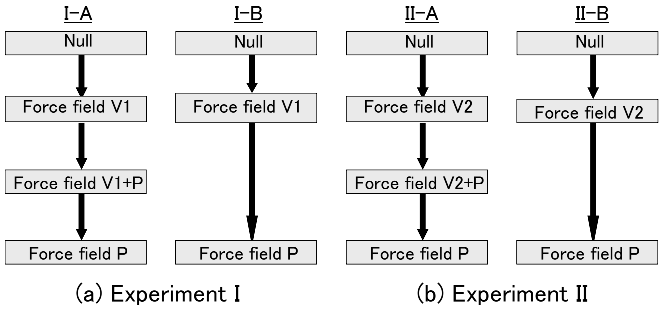
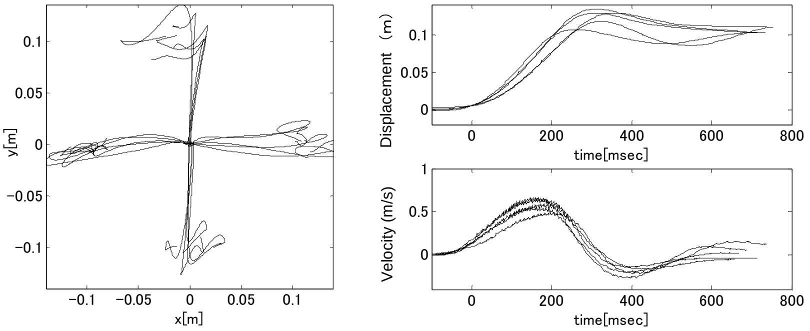
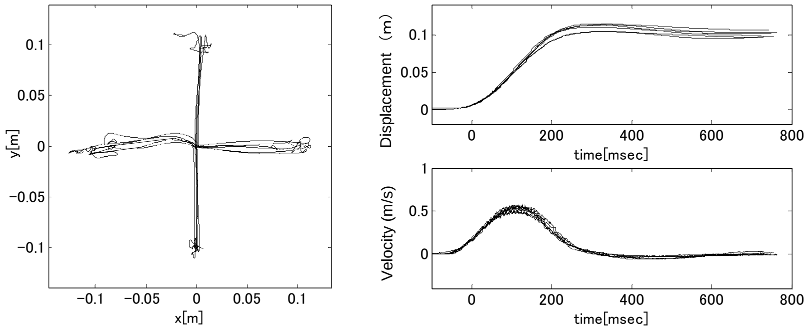



**Fig.4** Experiment procedure.



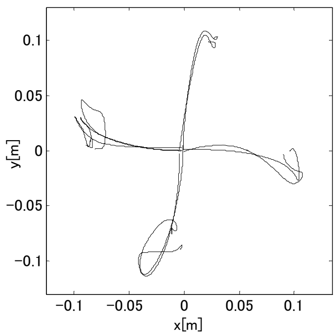

(a) Hand trajectories (b) Time profiles of displacement and velocity

A. at the beginning of learning for V1+P



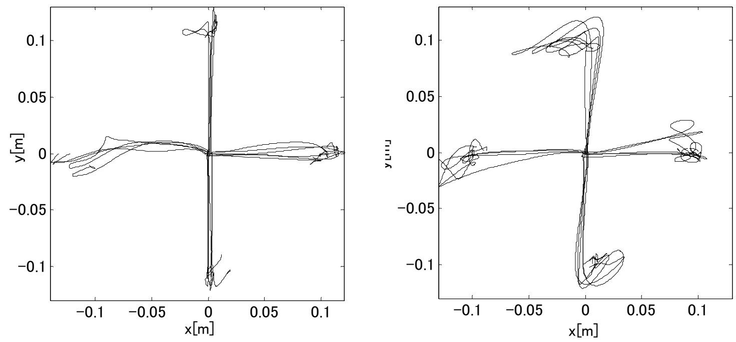

(c) Hand trajectories (d) Time profiles of displacement and velocity

B. at the end of learning for V1+P




C. After-effects

**Fig.5** Hand trajectories and time profiles of displacement and velocity at three stages of learning for the force field V1+P in Experiment I-A (Subject A).




(a) Experiment I-A (Subject A) (b) Experiment I-B (Subject B)

**Fig.6** Comparison between the hand trajectories at the beginning of learning for the force field P in Experiment I.

## 3. RESULTS

### *3.1. Experiment I*

Fig.5 shows the hand trajectory and time profile at three stages of learning for the environment dynamics V1+P in Experiment I-A for one subject. Fig.5-A and B denotes the beginning and end stages of learning. To examine the after-effects of learning the V1+P, the force field was unexpectedly removed on selected trials after learning, which is shown in Fig.5-C.

As seen in Fig.5(a), at the beginning of learning for V1+P, the hand trajectory is deviated from the straight line toward the target. Especially, the trajectories at the end of motion were shifted to the counterclockwise direction, which indicates that it is an unknown dynamics for the subject. Fig.5(b) shows the time profile of displacement and velocity. It is known that the profiles are disturbed each time by the force field.

On the other hand, when coming to the end of learning, the trajectory could be kept on the straight line to the target as shown in Fig.5(c). In addition, Fig.5(d) shows smooth and regular time profiles of displacement and velocity. Expressly, the velocity gives a bell-shape profile, which is the typical one after learning in the reaching motion. It indicates that the subject performs the reaching motion based on the identified environment dynamics V1+P. This is confirmed by the After-effect in Fig.5-C. The hand trajectories are curved to the clockwise direction even under no force field, which suggests that the reaching motion is performed by a feedforward manner based on the internal representation of the environment dynamics.

After the learning experiments for the force field V1+P, the subject was asked to perform the reaching motion under the force field P, which is a part of V1+P. The result is shown in Fig.6(a). It is seen that the trajectory is maintained on the straight line to the target even at the beginning of learning. The subject has experienced Null field, the force field V1, and the force field V1+P in serial order. It should be noted that even after learning the force field V1, the force field V1+P is equivalent to an unknown environment as seen in Fig6(a). However, after learning the force fields V1 and V1+P, the new force field P is not an unknown environment for the subject. That is, the subject could separately identify the force field P through those learning processes.

For the sake of comparison, the hand trajectory at the beginning of learning for the force field P in the experiment I-B is shown in Fig.6(b). The subject has experienced only the force field V1. As a result, the trajectories are disturbed toward the counterclockwise direction at the end of the reaching motion, which is almost same as Fig.5(a).

### *3.2. Experiment II*

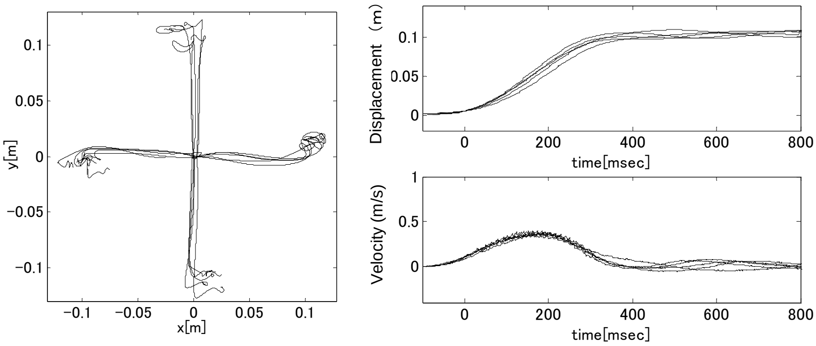
Next, we performed Experiment II-A where the first force field is V2. Fig.7 shows the hand trajectory and time profile at three stages of learning for the environment dynamics V2+P for one subject. Fig.7-A and B denotes the beginning and end stages of learning. To examine the after-effects of learning the V2+P, the force field was unexpectedly removed on selected trials after learning. The result is shown in Fig.7-C.

The learning process is almost same as Experiment I. the hand trajectory is slipped out from the straight line toward the target at the beginning of learning for V2+P as seen in Fig.7(a). The time profiles of displacement and velocity are disturbed by the force field (see Fig.7(b)).

After learning, as seen in Fig.7(c) and (d), the hand trajectories are kept on the straight line to the target and the time profiles of displacement and velocity are smooth and regular. The After-effect in Fig.7-C is also same as Experiment I.

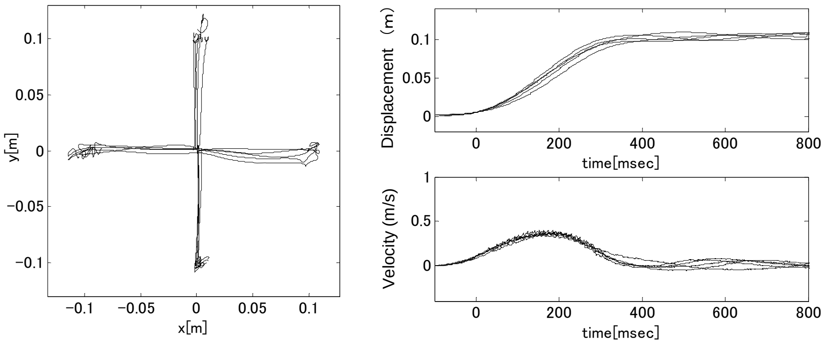
In the same way as experiment I, the subject was asked to perform the reaching motion under the force field P after the learning experiments for the force field V2+P. The result shown in Fig.8(a) is completely different from Experiment I. It should be noted that the hand trajectory is not maintained on the straight line to the target at the beginning of learning. The new force field P is an unknown environment for the subject.

For the sake of comparison, Fig.8(b) shows the hand trajectory at the beginning of learning for the force field P in the experiment II-B. The subject has experienced only the force field V2. The trajectory is almost same as Fig.8(a).



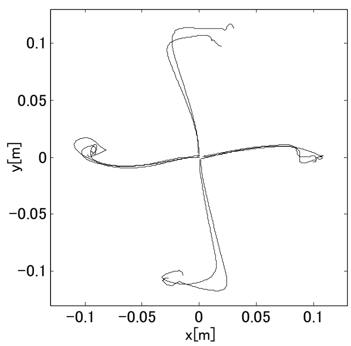

(a) Hand trajectories (b) Time profiles of displacement and velocity

A. at the beginning of learning for V2+P




(c) Hand trajectories (d) Time profiles of displacement and velocity

B. at the end of learning for V+P




C. After-effects

**Fig.7** Hand trajectories and time profiles of displacement and velocity at three stages of learning for the force field V2+P in Experiment II-A (Subject C).

## 4. DISCUSSION

In the experiment, we investigated whether humans could identify one side of dynamics from mixed force field in the case of having experienced either of them. The following three kinds of force field were given for the dynamic environments.

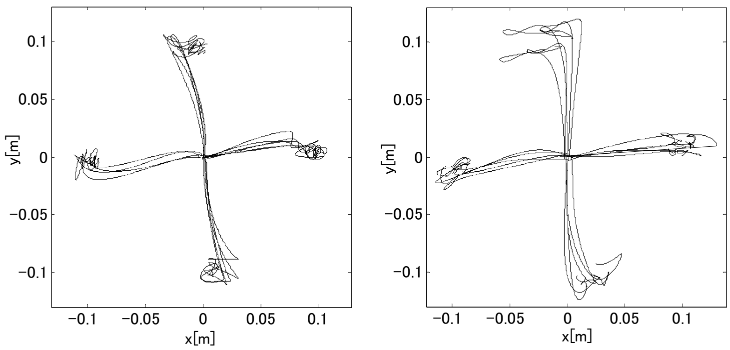
V1: Resistive viscosity force field.

V2: Counter clockwise rotational viscosity force field.

P : Clockwise rotational position dependent force field.

In Experiment I-A, the subject experienced V1, V1+P, and P in serial order. Then, the subject could perform the reaching motion smoothly along the straight lone to the target even at the beginning of learning for the force field P. The subject has never before experienced the force field P itself. It is therefore known that the subject separately identified the force field P during learning V1 and V1+P.

In Experiment II, the first force field V1 was changed into the rotational viscosity force field V2. Then, the subject could not identify the same force field P in spite of the same learning process. The difference between V1 and V2 is the direction of force vectors loaded to the subject during the reaching motion. V1 is a resistive force field and V2 is a




(a) Experiment II-A (Subject C) (b) Experiment II-B (Subject D)

**Fig.8** Comparison between the hand trajectories at the beginning of learning for the force field P in Experiment II.

counter clockwise rotational force field. The force vector in V1 is orthogonal to the force vector in P. On the other hand, the force vector in V2 points to the opposite direction against the force vector in P. Therefore, it is suggested that humans can separate the force field P from the mixed force field V1+P if V1 and P are orthogonal each other.

## 5. CONCLUSION

The present experiments suggest that the orthogonality of the force vectors loaded to the hand plays an important role to identify the environment dynamics. Though it is necessary to verify the various combinations of force fields, it is topics of much interest to connect with the spatial representation on sensory area through the somatosensory feedback.

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