Feedforward Adaptation to Stable and Unstable Dynamics in Arm Movements

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Abstract— In daily life, humans must compensate for the resultant forces arising from 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 the feedforward adaptation under a varying dynamical environment during reaching movements. Subjects first learned reaching movements in a position-dependent divergent force field (DF) and velocity-dependent force field (VF), and then in a switched force field SF1 (DF→VF) and SF2 (VF→DF). The experimental results show that the adaptation to the switched force fields has been achieved by combining the internal model-based control and the impedance control in a feedforward manner.

Keywords: feedforward adaptation, reaching movement, sensory-motor function, dynamical environment.

I. INTRODUCTION

In daily life, humans must compensate for the resultant forces arising from 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 [1][2]. For example, Shadmehr, Mussa-Ivaldi et al [3] have analyzed various reaching movements under velocity-dependent force field (VF) where the hand receives the external load in proportion to the hand velocity. It is then shown that humans compensate for the external load by the feedforward control based on the internal model. It is here called “internal model control”.

On the other hand, in manipulation tasks, such as opening a door, grasping a cup etc., the dynamic interaction between the human arm and external environment determines the stability of motion. Therefore, it has much importance to adjust the arm dynamics corresponding to the environment dynamics change. Any forces arising from interaction with the physical environment are dependent on the control of mechanical impedance in the human arm. Mechanical impedance is described by stiffness, viscosity, and inertia, which are a set of parameters for transforming the variables representing the motion (displacement, velocity, acceleration) into the force and torque. The arm impedance can be voluntarily changed based on the viscoelastic property of muscles, arm postures and feedback loop gains at the spinal cord level. Until now, the arm impedances under various conditions were identified, such as during maintained postures, during reaching movements [4]-[8], and in movements involving a given stable or unstable interaction.

Burdet et al [8] have analyzed the arm impedance during reaching movements under an unstable divergent force field (DF), which gives the external load to the arm in proportion to the hand deviation from the straight line between the starting and target points. Therefore, the subject is unable to predict the external load during the reaching movement and as a result, it is difficult to adopt the feedforward compensation based on the internal model. It has been demonstrated that the subject employed the strategy to raise the robustness to external fluctuations by the high arm impedance through the simultaneous activation of the agonist and antagonist muscles.

As mentioned above, previous researches have suggested that humans utilize two motor control mechanisms of internal model control and impedance control. An internal model controller computes feedforward commands of the joint torques for movement based on the estimated body-environment dynamics. An impedance controller adjusts the arm impedance mainly by co-contraction of agonist and antagonist muscles without changing the net joint torques, which is here called “impedance control”.

It has been shown that both controllers can operate simultaneously after motor learning [9]-[11]. Franklin et al have performed reaching movements under the velocity-dependent force field (VF) and divergent force field (DF) on each day after having learned the null field (free motion) and demonstrated that the subject could acquire each controller independently.

Now, in goal-directed movements, such as picking up a pebble under the swiftly running river, reaching and turning to the doorknob, we must construct a sequence of motor controls under different environment dynamics. Then it is not sufficient simply to use together the impedance control and internal model control, but it is required to combine both controls in a pre-programmed manner.

In order to simulate the above situations, in the present paper, we set up the external environments in which the velocity-dependent force field (VF) and divergent force field (DF) are switched reciprocally in the middle of reaching movement. Since the reaching movement is performed within hundreds msec, subjects...
are required to plan the impedance control and internal model control in a feedforward manner corresponding to changing environments. The present paper aims to verify experimentally how both the impedance control and internal model control are programmed to a varying dynamical environment and to discuss the control scheme realizing both control methods.

### II. REACHING MOVEMENT EXPERIMENT

#### A. Experimental set-up

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

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

The horizontal point-to-point arm movements were performed by the upper limb with three degrees of freedom. The movement distance was 0.2 m. The subject was instructed to reach the target from the initial position at a voluntary velocity within 600 msec. The hand, start and target positions were indicated on the display. The target circle is with the radius 25 mm.

#### B. Force field

As shown in Fig.2, the experiment examined the motor adaptation in four force fields: (a) position-dependent divergent force field (DF), (b) velocity-dependent force field (VF), (c) switched force field SF1 (DF→VF) and (d) switched force field SF2 (VF→DF).

The divergent force field (DF) gives the unstable external load to the arm in proportion to the hand deviation from the desired straight line (y-axis) as seen in Fig.2 (a), which is written as follows.

\[
F = \begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = \begin{bmatrix}
-k & 0 \\
0 & 0
\end{bmatrix} \begin{bmatrix}
dx \\
dy
\end{bmatrix} \quad [N], \quad k = 250 \text{ N/m}, \quad (3)
\]

where \(F = [F_x, F_y]^T\) is the hand load and \([dx, dy]^T\) is the hand deviation from the straight line.

The velocity-dependent force field (VF) is represented as follows.

\[
F = \begin{bmatrix}
13 & -18 \\
3 & 18 & 13
\end{bmatrix} \begin{bmatrix}
x \\
y
\end{bmatrix} \quad [N], \quad (8)
\]

where \([x, y]^T\) is the hand velocity. Then as seen in Fig.2 (b), the subject hand receives the external load to the upper left in proportion to the hand velocity during reaching movement to the front.

We set up dynamic environments where the force field is changed between the first and latter halves at the middle point \((y=0.1 \text{ m})\). The switched force field SF1 changes from the divergent force field (DF) to the velocity-dependent force field (VF). The switched force field SF2 inversely changes from the velocity-dependent force field (VF) to the divergent force field (DF).

#### C. EMG measurement

It is known that the viscoelasticity of muscles is variable in proportion to the muscle force. In order to investigate the impedance adjustment, we measured EMG signals on the following eight muscles as shown in Fig.3.

1. Shoulder joint muscles
   - Deltoid scapular part
   - Pectoralis major clavicular head
2. Elbow-shoulder double joint muscles
   - Triceps brachii
movements were performed for four days. The experiments for reaching D. level of the corresponding muscle. The EMG was A/D converted with the sampling signals was normalized by the maximum contraction filters (Cut-off frequency: 25 Hz). Then each of EMG trajectories in the VF were displaced to the right relative straight line similar to that in the DF. The after-effect behaviors. Subjects have already learned the divergent field (VF), (c) switched force field SF1 (DF→VF) and (d) switched force field SF2 (VF→DF). In each force field, movements are shown for the initial trials (first 5 times), the trials after learning (last 5 trials) and after-effect trials, and the hand forces $F_s$ after learning are shown on the right.

The initial trials in the divergent force field (DF) (Fig.4(a)) shows unstable behaviors, which diverged either to the right or to the left depending on the initial hand deviation. After practices of 100 times, however, subjects became skillful at producing straight trajectories along the y-axis. Then, the hand forces $F_s$ became very small during movements and was little affected by the divergent force field (DF).

On the other hand, initial movements in the velocity-dependent force field (VF) were systematically disturbed to the left by the external load as shown in Fig.4(b). After learning, however, the movement became to keep the straight line similar to that in the DF. The after-effect trajectories in the VF were displaced to the right relative to movements after learning. In addition, the hand force $F_s$ was directed to the right. That is, subjects in the VF learned to produce the force to compensate for the force field (VF) in a feedforward manner based on the internal model. In contrast, the after-effect trajectories in the DF were deviated very little from the y-axis, which means that subjects in the DF produced essentially the joint torques with less variance.

Next, let’s see the hand trajectories and forces in (c) switched force fields SF1 (DF→VF) and (d) SF2 (VF→DF) in Fig.4. The broken line at the middle indicates a switched point of the force field. The initial trials in both force fields SF1 and SF2 show unstable behaviors. Subjects have already learned the divergent force field (DF) and velocity-dependent force field (VF), but it is seen that mixed force fields SF1 and SF2 are unknown environments for the subject. After practices of 100 times, however, the movement became to keep the straight line similar to that in the DF and VF.

Further, the hand force $F_s$ was directed to the right at the first half of (c) SF1 (DF→VF) and at the latter half of (d) SF2 (VF→DF), which are similar to that of (b) the velocity-dependent force field (VF). On the other hand, the hand forces $F_s$ was very small during movements at the latter half of SF1 and at the first half of SF2. Thus, subjects changed smoothly the hand forces corresponding to the switched dynamics, and started to shift them before reaching the middle point. That is, it is known that after learning, the movement in switched force fields is programmed in a feedforward manner.

B. EMG

Fig.5 shows the rectified, averaged and smoothed EMG after learning about a typical subject A, which are the averages of five trials on DF and VF, and ten trials on SF1 and SF2. The horizontal axis indicates the normalized time by the movement time of each trial and the vertical axis indicates the EMG amplitude normalized by the
maximum contraction level of each muscle. The light gray portion shows the EMG of the free movement in the null field (NF) and the black area shows the EMG in the force filed.

In the divergent force field (DF), the extensor and flexor muscles in shoulder, elbow and wrist-elbow joints were co-activated from the beginning of movement, which means that the hand impedance was totally increased in the feedforward manner. On the other hand, subjects receive the external load to the upper left in the velocity-dependent force field (VF). Then, the extensor muscles in shoulder and elbow joints are remarkably activated.

In the switched force fields SF1, the coactivation level of all muscles was increased, especially at the latter half switched to the divergent force field (DF), which indicates the high hand impedance. In the switched force fields SF2, the coactivation level was similarly increased. Subjects receive the external load to the upper left in proportion to the hand velocity at the latter half. Therefore, the extensor and flexor muscles were strongly activated.
IV. DISCUSSION

It has been pointed out that there exists two motor control mechanisms of internal model control and impedance control and both controllers can operate simultaneously after motor learning [9]-[11]. In addition, the present experiments on switched force fields have suggested that subjects increase the hand impedance through the movement and incorporate the internal model control into the impedance control in a programmed manner. That is, the impedance and internal model controls can be programmed in a feedforward manner in adaptation to changing environments.

Fig. 6 shows a block diagram of motor control. The internal model controller has to acquire a neural representation of the external dynamics consisting of the body and environment.

The impedance control means that the body dynamics is adjusted corresponding to varying environments, i.e. the body dynamics changes with the environments. Therefore, the internal model within the controller has to be renewed with the impedance control. Even if subjects have learned the divergent force field (DF) and velocity-dependent force field (VF) independently, it is required to learn a new internal model in order to program the impedance control and internal model control. This is confirmed from the fact that the initial trials in the SF1 and SF2 were diverged either to the right or to the left.

In addition, the force field is switched on the way of movement in the SF1 and SF2. Therefore, the controller has to acquire a proper timing in the programmed sequence. Fig.4(c) and (d) show that the hand force $F_y$ is changed earlier than the middle point, which demonstrates that the motor program has been acquired corresponding to changing environments.

Now Fig. 7 shows a conceptual schema of motor control system, which is related to the impedance control, internal model control and motor program control. The hand impedance is synthetically controlled through the viscoelastic characteristics of muscle, the gain adjustment of spinal reflex system and the postural control of skeletal system [2]. The intermediate part and vermis of cerebellum play a major role in adjusting various parameters at the spinal cord level [2][12]. Further, the balance between the basal ganglia-brain stem route and motor cortex-brain stem route controls the muscle tonus level defining the hand impedance [13][14]. The experimental results suggest that these parameter adjustments are controlled in the feedforward manner corresponding to dynamic environments. It is then estimated that the impedance parameter is preset by the higher nerve center including the premotor cortex, supplementary motor cortex and motor cortex [1][2].

On the other hand, the lateral part of cerebellum has strong connection loops that receive the input from the motor related area (premotor cortex, parietal cortex,
motor cortex, etc.) in the cerebral cortex and return the output to the premotor cortex and motor cortex through the thalamus. The route between the cerebral cortex and lateral part of cerebellum contributes deeply to the internal model control [15][16].

In addition, the basal ganglia receives the input from the wide area in the cerebral cortex including the higher motor cortex, parietal cortex, prefrontal cortex, etc. and return the output to the cerebral cortex through the thalamus. It is considered that the route between the cerebral cortex and basal ganglia is closely related to construct the motor program [17]. The future problem is to analyze the system model among the impedance control, internal model control and motor program control, and connect them to each part of the motor related area [18]-[21].

V. CONCLUSION

The present paper analyzed the reaching movement under the environment where the stable velocity-dependent force field (VF) and unstable divergent force field (DF) were switched in the middle of movement. It was then demonstrated that subjects increased the hand impedance through the movement and incorporated the internal model control into the impedance control in suitable timing corresponding to varying environments. The smooth movement under dynamical environments is realized by preprogramming the impedance control and internal model control.

However, for example, Robo cup football needs to run in an open space based on the game situation. The above two controls are insufficient to realize such an intended action. In that case, it is desired to generate a suitable action based on the spatio-temporal context flows of the motor command and sensory feedback signals. Then, the hierarchical control structure will be required, such as the upper level generates an action sequence based on the context control and the lower level generates a motor pattern based on impedance control, internal model control and motor program control.

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