Predictive Adaptation to Dynamic Environments and Application to Motor Rehabilitation

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1. Introduction
   - Redundancy among Brain-Body-Environment
2. Experiments of arm reaching movements
   - Adaptation to dynamic environments-
3. EEG – FES system for stroke patients
4. Conclusion
Basic control mechanisms

Motor program

Motor learning & adaptation

Selection

Fine tuning

Somatosensory / visual feedback

Neural mechanisms for motor control

Cerebral Cortex

Basal ganglia

Cerebellum

Brainstem

Spinal cord

Musculoskeletal System

Somatosensory / visual feedback
Internal dynamics has much redundancy.

How to reduce redundancy of sensorimotor mapping?

It is required to adjust the internal dynamics before beginning voluntary movements.
Identification of external dynamics

Identification

Goal $y_d(t)$

Feedback Controller $G_c$

Feedforward Controller $G_F$

External Dynamics

Motor command $u(t)$

Motor output $y(t)$

Body $G_p$

Sensory feedback
Motor control

1) Simulation of body-environment dynamics
2) Prediction of sensory feedback
Conceptual control model of human movements

Feedforward & Feedback

- **Internal Model**
  - Prediction: $\hat{y}(t)$
- **Feedforward Controller**
- **Feedback Controller**

Target $y_d(t)$

Controller

Internal Dynamics

- **Body**
- **Arm Impedance**

External Dynamics

Efference copy $u(t)$

Sensory feedbacks $y(t - \Delta t)$

Time Delay

Sensory feedbacks $y(t - \Delta t)$

Feedforward & Feedback
Experiments of Arm Reaching Movements
-Adaptation to dynamic environments-
Adaptation to dynamic environments

**Arm Reaching Motion**

**Computational Model of Adaptation to Environments**
Modeling of motor adaptation and learning

**Unknown environments**

**Neuro-physiological Approach**
- Brain imaging during reaching motions
- Development of new equipments

\[ M(\theta)\ddot{\theta} + h(\theta, \dot{\theta}) = \tau - J(\theta)^T F_e \]
Velocity-dependent force field (VF)

\[
\begin{bmatrix}
  F_x \\
  F_y 
\end{bmatrix} = \begin{bmatrix}
  \dot{x} \\
  \dot{y}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  13 & -18 \\
  18 & 13
\end{bmatrix} \begin{bmatrix}
  \dot{x} \\
  \dot{y}
\end{bmatrix}
\]

(by Shadmehr, 1994)
Hand trajectories and hand force

Hand trajectories and hand force
Hand trajectories and EMG during reaching motion

(a) Hand trajectories

Target (45°)
1st time
72nd time
Initial position

(b) Biceps
Last 8 times
Modified
First 8 times

(c) Triceps
Free motion

EMG (average of 24 subjects)
(by Shadmehr, 1999)
Unstable (divergent) force fields (DF)

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = \begin{bmatrix}
\beta dx \\
0
\end{bmatrix} \quad \beta > 0
\]

(E. Burdet et al, Nature, 2001)
Hand trajectories and forces in DF

Hand trajectories

Hand force

Initial trial

After learning

After effect

Fx [N]

After learning
Muscle activities (EMG) during reaching motions

The subject plans the muscle activities before beginning the reaching motion.

EMG under After-effects is similar to the unstable force field.

* : $P<0.05$, ** : $P<0.01$, *** : $P<0.001$

(Franklin, Exp Brain Res., 2003)
1) We plans **Internal Model Control** before beginning the reaching movements under the dynamic environment.

2) We presets **Impedance Control** before beginning the reaching movements.

**Question?**

*Can we program the *internal model control* and *impedance control* in a feedforward manner?*
Switched force fields

(a) SF1 (VF → DF)

(b) SF2 (DF → VF)
Impedance Adaptation

Internal Model Adaptation

The impedance and internal-model controls are programmed in a feedforward manner in adaptation to the contexts of dynamic environments.

Program Adaptation

Internal Model Adaptation

Impedance Adaptation
Experimental results suggest that the predictive adaptation to the environment dynamics is composed of three levels:

1. Impedance adaptation → Parameter adaptation
2. Internal model adaptation → State dynamics adaptation
3. Program adaptation → Context adaptation
Motor adaptation mechanisms

**Internal model adaptation**
- Cerebral cortex
- Supplementary motor area
- Prefrontal cortex
- Premotor cortex
- Motor cortex
- Parietal cortex
- Basal ganglia

**Program adaptation**
- Motor Controller
- Intermediate part & vermis

**Cerebellum**
- Lateral part

**External dynamics**
- Environment
- Limb/Body
- Muscle viscoelasticity
- Spinal reflex system

**Brain stem-Spinal system**

**Impedance adaptation**
Electroencephalogram (EEG) – Functional Electrical Stimulation (FES) System for Stroke Patients
It is not strictly to recover the motor performance as it was, but reconstruct optimal motor performance in the new situation → Re-optimization.
Motor intention and sensory feedback for motor rehabilitation

Motor Intention

Prefrontal motor cortex

Parietal cortex

Primary motor cortex

Primary somatosensory cortex

Brain stem- Spinal system

Basal ganglia & Cerebellum

Proprioceptive feedbacks

Visual & Auditory feedbacks

Motor command
## Reconstruction of motor function

<table>
<thead>
<tr>
<th></th>
<th>EEG-BCI</th>
<th>EEG-FES</th>
<th>EMG-FES</th>
<th>Leg powered wheelchair</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
<td>Spinal injury (paraplegia)</td>
<td>Spinal injury / stroke (paraplegia)</td>
<td>Stroke (hemiplegia)</td>
<td>Stroke (hemiplegia)</td>
</tr>
<tr>
<td><strong>Object</strong></td>
<td>Transmission of intention</td>
<td>Transmission of motor intention</td>
<td>Reconstruction of motor function</td>
<td>Reconstruction of motor function</td>
</tr>
<tr>
<td><strong>How to</strong></td>
<td>Detect the motor intention from EEG at the motor imagery of arm or leg</td>
<td>Regain movements based on the motor intention from EEG at the motor imagery of arm or leg</td>
<td>Activate the muscles by FES based on the motor intention from EMG</td>
<td>Realize the somatosensory feedback by pedaling the wheelchair</td>
</tr>
<tr>
<td><strong>Advantage</strong></td>
<td>Voluntary EMG is not required</td>
<td>Learning effects of voluntary somatosensory feedbacks</td>
<td>Learning effects of somatosensory feedbacks &amp; enhancement of motivation</td>
<td></td>
</tr>
<tr>
<td><strong>Weak points</strong></td>
<td>Not motor learning</td>
<td>Difficult to detect motor intention from EEG</td>
<td>Voluntary EMG activity is required.</td>
<td>Effect on gait disorder is not clear.</td>
</tr>
</tbody>
</table>
Proposed EEG-FES system for motor rehabilitation

**EEG**

- Motor Intention

**FES**

- Muscle Actuation

- Basal ganglia
- Cerebellum
- Motor cortex
- Premotor Cortex & Supplementary motor area
- Parietal cortex
- Somatosensory area
- Proprioceptive feedback
- Brain stem-Spinal system
- Environment
- Musculo-Skeletal system

Sensory feedback
Event Related Desynchronization (ERD)

- **The characteristics of ERD are as follows.**
  - Decreasing of electric potential in specific frequency band (alpha (8-15Hz), beta (15-35Hz) band)
  - Observed during motion and motor imagery
  - Activation of cortico-thalamus loop? (Lopes da Silva, 1991)

- **ERD detection.**
  - Band pass filtered (25-30Hz)
  - Full wave rectified and 50 times sum averaged
Basic Experiments
Experimental setup

- EEG measurement during FES activation on both quadriceps.
  - 17 healthy subjects participated in the experiment.
  - EEG from 7 electrodes (around Cz area) were measured.
  - One task consisted of 50 trials of FES.
Frequency analysis

- The data for each 3 seconds is divided into 500 msec data.
- After converting to frequency space, the ensemble average is calculated.
- To quantify the amount of ERD, $r^2$ value was calculated for the frequency band for 24 – 26 Hz.
Power spectrum before and after motor imagery training

(a) Before training

No motor imagery
Motor imagery

(b) After 3 days training

No motor imagery
Motor imagery
**r² value**

- r² value is used to calculate the amount of ERD (This method is popular in BCI researches).
- r² value uses the within- and between- variance with two groups.
- Larger r² value mean the clearer detection of ERD.

\[
r^2(x, y) = \frac{\frac{(\sum x)^2}{n_x} + \frac{(\sum y)^2}{n_y}}{\frac{\sum x^2 + \sum y^2 - b}{n_x + n_y}} - b
\]

where:

\[
b = \frac{\sum x^2 + \sum y^2}{n_x + n_y}
\]
Training effects of $r^2$ value

<table>
<thead>
<tr>
<th></th>
<th>Before training</th>
<th>1st day</th>
<th>2nd day</th>
<th>3rd day</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r^2$ value</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

* $p<0.05$
Training results of a stroke patient
Experiment set-up

- **Subject**: Brain stem infarction. 30 months after stroke.
- **Paralyzed on the left side of the body** *(Foot-pat test: 0/6)*
Experiment

5 min.  30 min.  5 min.
Training by EEG-FES system

Intend to move left foot

ERD 500 msec

Sensory feedback

FES output [mA]

FES output [mA]
Before Training
(15 seconds)
After Training
(15 seconds)
Leg movements

Before training

Knee joint

After training

Ankle joint
Statistical significance of ankle joint movements

(a) Paralyzed side

(b) Normal side
Ankle joint movements

Before training
Paralyzed side

Normal side

After training
Muscle activity levels

Before training

Paralyzed side

Normal side

After training

Electric potential [µV]

Time [sec]
Statistical significance of muscle activities

(a) Paralyzed side

(b) Normal side
Brain image

Brain stem
Conclusion

Motor Intention
New non-invasive brain activity measurement

EEG-FES System
Sensory Feedbacks
Robotics
Haptic devices
Variable impedance

EEG
FES
Sensory feedbacks
Motor intention and sensory feedback for motor rehabilitation

Motor Intention

Primary motor cortex

Prefrontal motor cortex

Parietal cortex

Primary somatosensory cortex

Basal ganglia & Cerebellum

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Sensory feedbacks

Motor command
Joint researches with

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