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MUSCULAR SENSATION INDUCE EVEVT RELATED DESYNCHRONIZATION (ERD) ON FOOT MOTOR AREA

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Abstract − Strokes are a leading cause of adult disabilities, and training in voluntary movement has been effective in rebuilding the motor skills of stroke patients. We are developing an EEG-FES system that can assist in the reconstruction of a closed loop between motor commands and sensory feedback in stroke patients. The system uses event-related desynchronization (ERD) to reflect motor intentions. We did a pilot study on ERD before applying for stroke patients. This study focused on how FES (sensory feedback) affects ERD. Research has showed that sensory feedback affects ERD, but it is unclear which sensory inputs (tactile, muscular, tendinous, or articular) are the main causes. We examined how ERD is affected by functional electrical stimulation (FES) of both feet of healthy subjects. The results indicated that the ERD increased as the FES was increased. The ERD was greater under the leg-free condition than under the leg-fixed condition, which suggests that muscular and articular sensations induce ERD in the foot motor area (Cz). This results show that our EEG-FES system can be applied for the rehabilitation of stroke patients.

Keywords: Event Related Desynchronization (ERD), Functional Electrical Stimulation (FES)

1. INTRODUCTION

Strokes are a leading cause of adult disabilities. Impairments due to stroke can induce functional deficits in motor control. Physical therapy, which involves a therapist bending and stretching a patient's paralyzed limbs to prevent muscle contracts, is the most common method of rehabilitation for stroke patients. Recently, brain imaging technologies such as computed tomography, functional magnetic resonance imaging, and positron emission tomography have been used to pinpoint the relationships between deficit areas and motor disabilities. Some researchers are trying to reconstruct motor functions by stimulating peripheral nerves around the deficit areas. For example, functional electrical stimulation (FES) is effective because it enhances facilitation. FES elicits the action potential in the motor nerves innervating the paralyzed muscles. Reports have shown that FES can be used to reconstruct skills needed for movements in daily life, such as standing up and cycling [1,2]. This stimulation creates neuron branches. Some medical doctors are

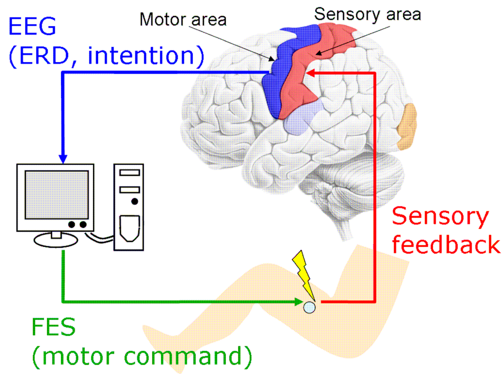


Fig. 1. Conceptual loop of proposed system.

advocating the importance of neural reconstruction as it relates to motor learning. They emphasize the necessity of functional training which can reflect a patient's intention.

In terms of motor control, motor planning generated from the premotor cortex, supplementary motor area, and basal ganglia is transferred to the motor area. Then, motor commands are generated from the motor area in cooperation with the cerebellum. Finally, motor commands stimulate muscles [3]. In this case, motor planning from the premotor cortex and sensory feedback from the peripheral nerves are necessary to promote motor learning. However, stroke patients can neither send motor commands to muscles nor receive sensory feedback.

We propose a rehabilitation system that combines motor commands with sensory feedback (Fig. 1). The EEG of the motor command (motor intention) is extracted from the motor area, while FES is applied to the paralyzed muscles in synchronization with motor command appearance. We believe that this system will accelerate motor recovery by enhancing motor learning and also that it can be part of an effective rehabilitation system for severely affected stroke victims.

We focused on event related desynchronization (ERD) as a motor command. ERD is a phenomenon in which alpha and/or beta band voltages decrease as the number of synchronized neural assemblies increases. It is generally thought that alpha and beta ERD occurs before and during motor execution or motor imagery [4]. Before applying our system to stroke patients, we examined healthy subjects to determine the effect of FES (sensory feedback) on ERD

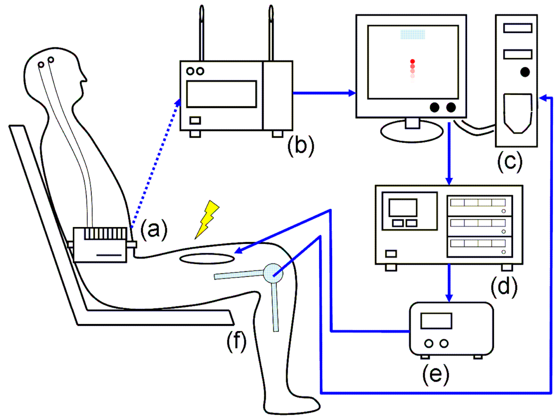


Fig. 2. Experimental system: (a) multi-telemeter system (sender), (b) multitelemeter system (receiver), (c) PC with A/D and D/A converter, (d) electricalstimulator, (e) isolator, and (f) goniometer.

appearance.

Previous studies have shown that ERD can be induced by sensory feedback from peripheral nerves [5]. Gaetz et al. showed that cutaneous stimulation with a toothbrush can induce ERD in each motor area [6]. They stimulated the fingers and toes of healthy subjects [7] and measured ERD by magneto encephalography (MEG). They also used FES to induce wrist flections, which induced ERD in the arm motor area. In FES, electrical pulses are applied to muscles, which causes the muscle fibers to contract. This causes joint movement. This stimulus causes many kinds of sensory feedbacks including muscular, tendinous, joint, and cutaneous sensation. Previous research has not explained which sensory feedback is the main cause of ERD. In our proposed system, motor commands and sensory feedback make a closed loop in the brain. We needed to confirm that sensory feedback from muscular sensations (muscle spindle) causes ERD in the motor area.

Therefore, we examined two things regarding the effect of sensory feedback on ERD: can ERD be induced by applying FES to the quadriceps and which sensation mainly causes ERD in the foot motor area?

2. METHOD

2.1. Experimental task

Seventeen healthy subjects participated in this experiment. During the task, they remained in a relaxed state. The EEG data were measured while they gazed at the computer screen (there was no motor imagery or other specific brain activity). During the first three seconds, FES was not applied to the muscles, after which it was applied to both sides of the quadriceps for three seconds. During the stimulation, a red visual cue was presented on the computer screen. This 6-s trial was repeated 50 times.

2.2. Experimental setup

Fig. 2 shows the PC and interface used in this study. Continuous EEG signals were recorded by a multi-telemeter system (WEB5000, Nihon Koden, (a,b) in Fig. 2) and transferred to the PC ((c) in Fig. 2), which was equipped with an A/D converter (PCI-3135, Interface). In the FES experiment, electrical stimulators (SEN-8203, Nihon Koden, (d) in Fig. 2) with isolators (SS-104J, Nihon Koden, (e) in Fig. 2) were connected to a D/A converter (PCI-3325, Interface) mounted on the PC. A goniometer (45161, SANEI, (f) in Fig. 2) was attached to the right knee to measure knee motion. Visual Studio 2005 was used to control the D/A converter and visual cues in Windows XP.

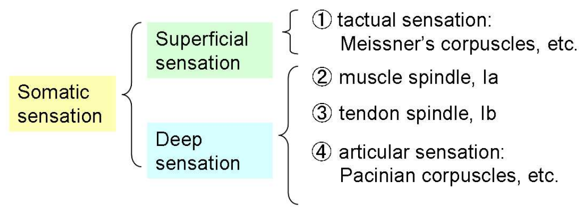


Fig. 3. Classification of somatic sensation.

2.3. Measurement of EEG

EEG signals were recorded by using Ag-AgCl electrodes (NE-512G, Nihon Koden) attached to seven scalp sites (national 10-20 method, Cz, FCz, CPz, Pz, and between them). A reference electrode was placed on the right ear (A2) and a body ground was placed on the left ear (A1). The sampling frequency was 256 Hz. All EEG signals were filtered between 0.1 and 100 Hz in the data acquisition phase.

2.4. FES condition

We applied FES to both sides of the quadriceps through FES electrodes (EW 0601P, National) attached 10 and 25 cm from the knee. Stimulation power was adjusted for each subject to accommodate different fat and muscle structures. The maximum FES current was 30 mA, the stimulation frequency was 50 Hz (20 msec), and the stimulation width was adjusted to a 30-degree extension of the knee angle. As a result, the stimulation duration was 180-300 μs. Fig. 7 shows the two FES patterns: (a) constant FES current (30 mA) and (b) ramp FES current (ramp change). The stimulation conditions were different for each stimulation pattern. First, during the leg-free condition, the stimulation duration was changed from a normal condition (FES normal, 180-300 μs) to a 1/3 condition (FES 1/3, 60-100 μs). In the 1/3 condition, no leg extension occurred. Next, during the normal stimulation condition (180-300 μsec), there were two leg conditions: a leg-free condition that resulted in a 30-degree knee extension and a leg fixed condition (no knee extension).

2.5. Somatic sensation

Fig. 3 shows the simplified classification of a somatic sensation. Somatic sensation can be classified as either a superficial or a deep sensation. Superficial sensation is mainly a tactual sensation, and there are sense organs including Meissner's corpuscles and Merkel cells. Deep sensation, in contrast, consists of a muscular sensation from the muscle spindle, a tendinous sensation from the tendon spindle, and an articular sensation from the Pacinian corpuscles, etc. This experiment focused on two aspects. 1) The effect of tactual sensation and muscular sensation was

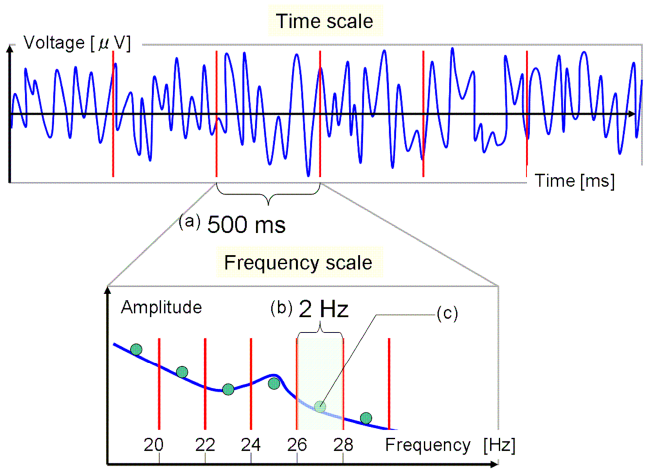


Fig. 4. Frequency analysis method.

examined by changing the stimulation duration (FES normal vs. FES 1/3). In the FES 1/3 condition, the stimulation was mainly related to tactual sensation. In the FES normal condition, the stimulation was not only for tactual sensation, but also muscular sensation. 2) Deep sensations were examined by changing the leg condition (leg free vs. leg fixed). In the leg-free condition, muscular sensation and articular sensation were mainly affected by knee extension. In the leg-fixed condition, tendinous was mainly affected by isometric contraction.

2.6. Performance evaluation

2.6.1. Frequency analysis

Fig. 4 illustrates the frequency analysis method. First, for determining the presence or absence of FES, the continuous EEG data were divided into 500-ms data sets (Fig. 4(a)). These sets were converted into frequency data, and segmented into 2-Hz intervals (Fig. 4(b)). In each frequency segment, the 300 (50 points * 6 divisions) data points were sum-averaged.

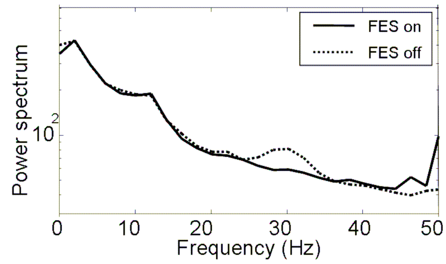
2.6.2. r2 value

As a quantitative measure of the difference (presence or absence of FES), the r2 value (Equation (1) and (2)), which is widely used in BCI research, was used [8]. The *x* and *y* represent the data classes (for example, x represents the presence of FES (28-30 Hz), y represents the absence of FES (28-30 Hz)) and n_x, n_y represent the quantity of data.

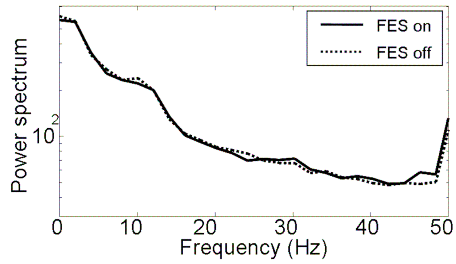
$$r^2(x,y) = \frac{(\sum x)^2 / n_x + (\sum y)^2 / n_y - G}{\sum x^2 + \sum y^2 - G} \qquad (1)$$

$$G = (\sum x + \sum y)^2 / (n_x + n_y) \qquad (2)$$

The r2 value was used to calculate within and between the variances of each class. An increase in the r2 value indicated a greater difference, i.e. greater ERD ($-1 \leq$ r2≤ 1).

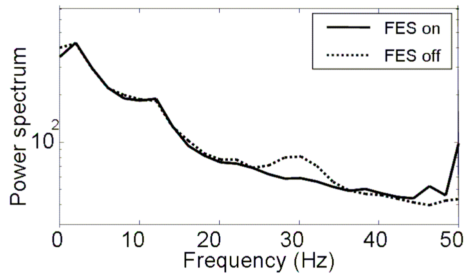


(a) normal stimulus duration.

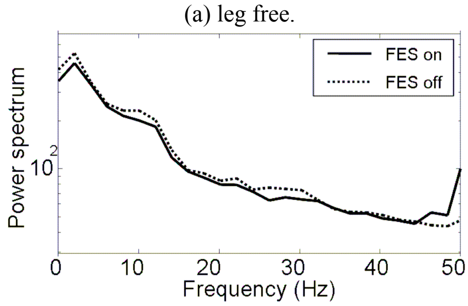


(b) 1/3 stimulus duration.

Fig. 5. Average power spectra of stimulus duration change (FES constant, subject A, Cz area).



(a) leg free.



(b) leg fixed.

Fig. 6. Average power spectra for different leg conditions (FES constant, subject A, Cz area).

2.6.3. Band power

Band power evaluation was used to visualize the FES effect on a time scale [9]. First, the optimal frequency bands and electrodes were determined for each subject. One trial EEG data (six seconds: first 3 seconds - absence of FES, last 3 seconds - presence of FES) was filtered in the optimal frequency band. After that, we calculated the root mean square with a 0.125-s window and a 0.0625-s shift. Finally, all EEG data were sum-averaged (50 times).

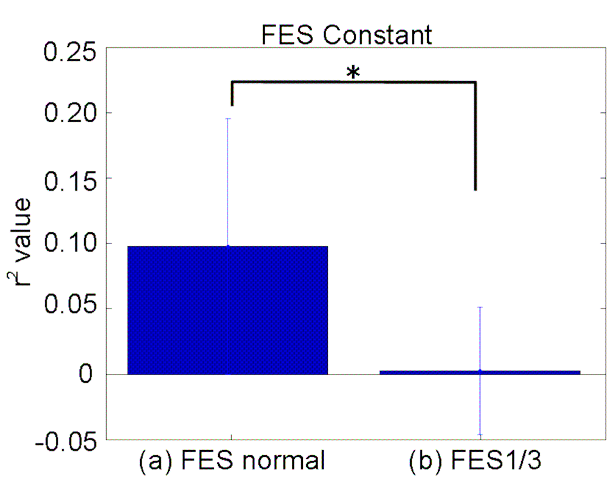


Fig. 7. r2 value: (a) FES normal, (b) FES 1/3 (17 subjects, FES constant).

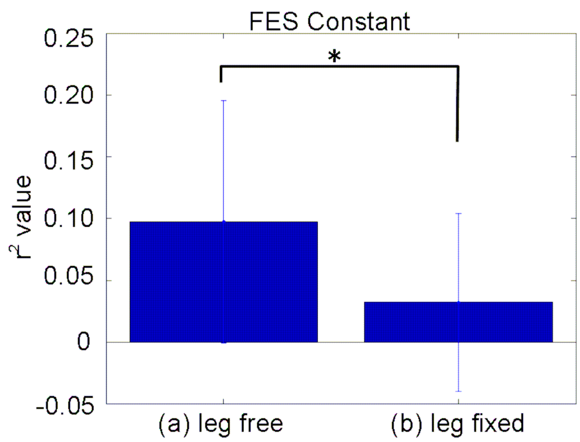


Fig. 8. r2 value: (a) leg free, (b) leg fixed (17 subjects, FES constant).

3. RESULT

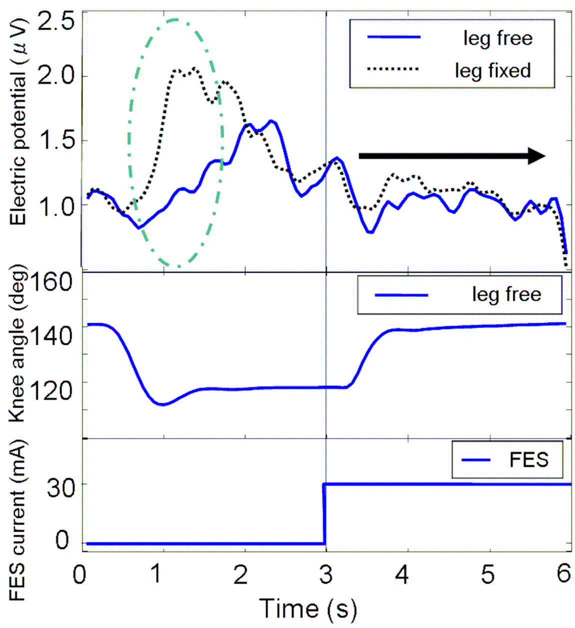
3.1. Power spectrum

Fig. 5 shows the sum-averaged power spectrum for the different stimulation durations (FES constant, Cz area, subject A). Comparison of the FES normal (Fig. 5(a)) with FES 1/3 (Fig. 5(b)) reveals ERD around 30 Hz under the FES normal condition.

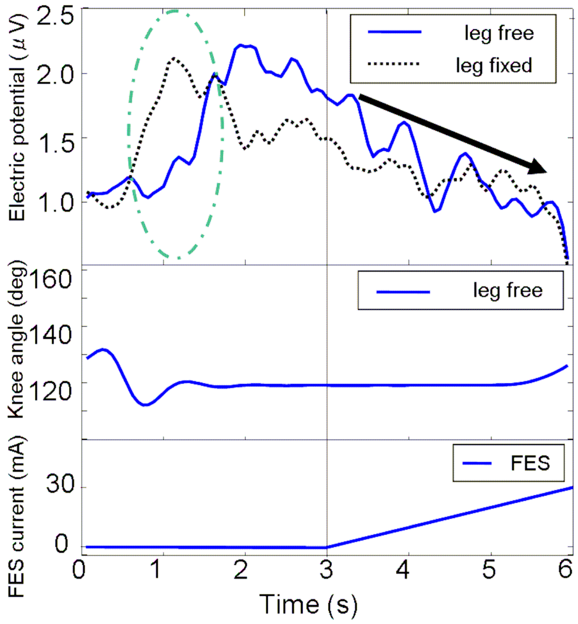
Fig. 6 shows the sum-averaged power spectrum for the different leg conditions (FES constant, Cz area, subject A). Fig. 6(a) shows the ERD for the leg-free condition, and Fig. 6(b) shows it for the leg-fixed condition. ERD can be seen at around 30 Hz under both conditions, but clear ERD can be seen under the leg-free condition.

3.2. r2 value

Fig. 7 shows the r2 value for the two stimulation durations (17 subjects, average and variance, FES constant).



(a) constant current FES.



(b) ramp current FES.

Fig. 9. Time record of averaged band power, knee angle, FES current (subjectB, Cz area).

There is a significant difference between the FES normal condition and the FES 1/3 condition ($p<0.05$).
Fig. 8 shows the r2 value for the two leg conditions (17 subjects, average and variance, FES constant). Again there is a significant difference between the leg-free and leg-fixed conditions ($p<0.05$), but the difference is smaller than the one shown in Fig. 7.

3.3 Band power

Fig. 9 shows the band power sum-average waveforms for the (a) FES constant and (b) FES ramp change conditions (subject B, Cz area). The upper plot shows the band power (electrical potential, μV). The middle plot shows the knee angle for the leg-free condition (deg), and the bottom plot shows the FES current change (mA). For this subject, the EEG data was filtered between 27 and 31 Hz. From 0 seconds to 3 seconds, there was no FES, and from 3 to 6 seconds, there was FES.

For the FES constant condition (Fig. 9(a)), the ERD seems to have been constant during the FES. For the FES ramp change (Fig. 9(b)), it changed as the current was changed.

4. DISCUSSION

During the stimulation of the quadriceps (which caused knee extension of 30 degrees), ERD could be seen in the foot motor area. In this case, both superficial sensation (tactual sensation) and deep sensation (muscular, articular sensation) were stimulated. In contrast, ERD could not be seen when the stimulation duration was reduced to 1/3 (FES 1/3). There was no knee extension because there was insufficient muscle contraction. This means the stimulation resulted in superficial sensation, not deep sensation.

After the knee extension (0-1.5 s), ERD could be seen (Fig. 9). During this time, the knee angel was on its way back to a normal position, and muscular and articular sensation returned to the brain. As a consequence, feedback from deep sensation (muscular, tendinous and articular sensation) was the main cause of ERD, and there was little effect from superficial sensation (tactual).

Under the leg-fixed condition, there seems to have been some feedback from muscular and articular sensation because of the isometric contraction. Under this condition, ERD could be seen on some level, but there was less ERD than under the leg-free condition (Fig. 8, 9). This implies that muscular and articular sensation mainly affects the emergence of ERD.

Under the ramp change condition for the FES current (Fig. 9(b)), ERD decreased as the FES current was increased. This was true for both the leg-free and leg-fixed conditions. In addition, ERD could be seen before the extension of the knee. Thus, FES may stimulate not only muscular and articular sensation but also directly stimulates nerve fibers like Ia and Ib.

There were significant differences between the subjects used in this experiment (Fig. 7, 8). There were also many factors, including stimulation duration and muscle position. From future work, we need to develop methods that can reduce individual variances.

5. CONCLUSIONS

We conducted two fundamental experiments on an electroencephalogram (EEG) - Functional electrical stimulation (FES) system. we examined the sensory feedback effects of FES. The results suggest that feedback from muscular and articular sensations affect ERD appearance in the foot motor area. This means that the proposed system may assist in the motor recovery of stroke patients by reconstructing the closed between motor commands and sensory feedback.

Our next goal is to further develop the EEG-FES system and evaluate its potential as a rehabilitation tool for stroke patients.

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REFERENCES

[1] Robert Riener, Maurizio Ferrarin, Esteban Enrique Pavan, Carlo Albino Ferigo, "Patient-Driven Control of FES-Supported Standing Up and Sitting Down: Experimental Result", IEEE Transaction On Rehabilitation Engineering, 8, 4, 523-529, 2000

[2] Jia-Jin J. Chen, Nan-Ying Yu, Ding-Gau Huang, Bao-Ting Ann and Gwo-Ching Chang, "Applying Fuzzy Logic to Control Cycling Movement Induced by Functional Electrical Stimulation", IEEE Transaction On Rehabilitation Engineering, 5, 2, 158-169, 1997

[3] Koji Ito, "Systems theory of embodied motor intelligence motor learning and control for human robotics", Kyoritsu Pub, 2005 (in Japanese)

[4] Claudio Babiloni, Filippo Carducci, Febo Cincotti, Paolo M. Rossini, Christa Neuper, Gert Pfurtscheller, and Fabio Babiloni, "Human Movement-Related Potentials vs. Desynchronization of EEG Alpha Rhythm: A High-Resolution EEG Study", Neuroscience Letters, 239, 65-68, 1997

[5] Alegre M. et al., "Beta electroencephalograph changes during passive movements: sensory afferences contribute to beta event-related desynchronization in humans", Neuroscience Letters, 331, 29-32, 2002

[6] William Gaetz and Douglas Cheyne, "Localization of sensorimotor cortical rhythms induced by tactile stimulation using spatially filtered MEG", NeuroImage, 30, 899-908, 2006

[7] Gernot R. M¨uller et al., "Event-related beta EEG changes during wrist movements induced by functional electrical stimulation of forearm muscles in man", Neuroscience Letters, 340, 143-147, 2003

[8] Hesham Sheikh et al., "Electroencephalographic(EEG)-based communication: EEG control versus system performance in humans", Neuroscience Letters, 345, 89-92, 2003

[9] Patrice Clochon et al., "A new method for quantifying EEG event-related desynchronization: amplitude envelope analysis", Electroencephalography and clinical Neurophysiology, 98, 126-129, 1996