A Measurement of Lower Limb Angles Using Wireless Inertial Sensors during FES Assisted Foot Drop Correction with and without Voluntary Effort

Takashi Watanabe, Shun Endo, Katsunori Murakami, Yoshimi Kumagai, and Naomi Kuge

Abstract—**An integrated wireless system of lower limb angle measurement and Functional Electrical Stimulation (FES) control was developed in our previous study for application to motor rehabilitation. In the motor rehabilitation, it is also considered that voluntary effort to move their limbs is effective. In this paper, gait movements of a hemiplegic subject were measured with and without voluntary effort of ankle dorsiflexion during FES assisted foot drop correction as a preliminary test for gait rehabilitation with FES. Some characteristics of hemiplegic gait and differences in joint angles between the paralyzed and the non-paralyzed sides were found in the measurement. The foot and the shank inclination angles at the toe off timing showed small change with the voluntary effort of dorsiflexion during FES control. In addition, variations of the inclination angles of some segments of the paralyzed side were larger than those with only FES at the toe off timing, maximum angle point and the foot contact timing in the case of the voluntary effort. These results suggested that voluntary effort could change movement in FES control. However, these changes with voluntary effort were not seen with larger stimulation intensity. Therefore, it was considered that the movement changes with voluntary effort were small because the subject could not produce further voluntary muscle force in excess of the muscle force production by FES. It would be necessary to determine appropriate intensity of electrical stimulation for rehabilitation use.**

Index Terms—**Functional electrical stimulation, FES, rehabilitation, voluntary effort, foot drop, angle, inertial sensor.**

I. Introduction

Functional electrical stimulation (FES) has been focused in motor rehabilitation, because FES has therapeutic effects in addition to functional effects [1]. Improvement of muscle strengthening and prevention of muscle atrophy have been reported for over 30 years. Improvement in motor and walking ability [2], [3], a possibility of improving gait pattern [3], and motor recovery of upper limb [4] have also been reported as the therapeutic effects of FES. Furthermore, FES therapy has been found to reduce disability and improve voluntary grasping beyond the effects of conventional upper extremity therapy [5]. The combination of voluntary effort and FES has also been suggested to have great potential to induce plasticity in the motor cortex and to be an effective approach in rehabilitation after stroke [6].

Motor function of lower limb is important for daily living. That is, rehabilitation training or daily exercise of lower limb function is necessary for motor disabled subjects or elderly persons. In the rehabilitation training, evaluation of motor function of subjects is essential. In case of using FES in the rehabilitation, changes of movement by using FES have to be made clear. However, since FES control of a specific joint movement of lower limbs may have some effects on other joint movements of the limbs throughout the body, it is preferable to measure movements of the paralyzed and non-paralyzed parts of the body for objective and quantitative evaluation in rehabilitation training. Even in a simple control of a joint movement by FES, it is considered that effects of FES control differ between subjects. Evaluation of movements would be desirable in order to get appropriate FES effect and rehabilitation training effect.

In our previous study, an integrated wireless system of the lower limb angle measurement and FES control was developed [7]. In order to support gait rehabilitation, FES control was designed for correcting the foot drop of a hemiplegic patient. In this paper, gait movements of a hemiplegic subject were measured with and without voluntary effort of ankle dorsiflexion during FES assisted foot drop correction as a preliminary test of gait rehabilitation with FES. Changes of the movement of the lower limbs induced by electrical stimulation and effects of the voluntary effort were discussed.

II. Methods

A. Measurement and Control System

The integrated wireless system of lower limb angle measurement and FES assisted foot drop correction consisted of seven wireless inertial sensors (WAA-006, Wireless Technologies), a wireless surface electrical stimulator and a notebook computer (Fig. 1). The sensors were attached on the feet, shanks, and thighs of both sides and the lumbar region using stretching bands. Acceleration and angular velocity signals of the wireless inertial sensors were measured with a sampling frequency of 100 *Hz* and recorded in the PC. Stimulation data were transmitted to the surface electrical stimulator through the 2.4 *GHz* wireless transceiver modules from the PC. The wireless surface stimulator operated in 2 AAA batteries, which was developed in our laboratory based on [8], generates electrical stimulation pulses immediately after receiving the stimulation data.

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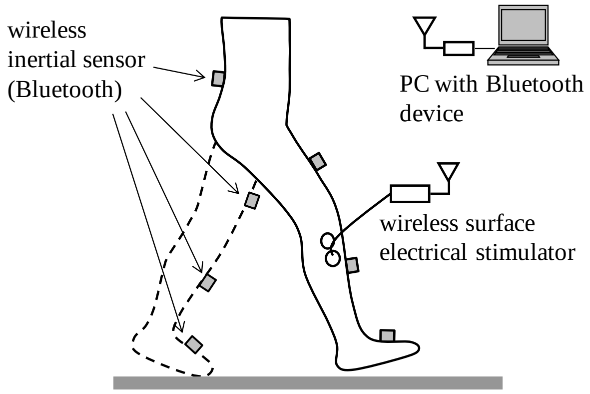


Fig. 1. Outline of an integrated wireless system of FES control and movement measurement.

Stimulation timing was determined by the acceleration (longitudinal axis) and the angular velocity signals measured with the inertial sensor attached on the shank of the hemiplegic side. The first step of the hemiplegic side was not assisted by FES because it was used to detect the beginning of the gait. That is, the first swing was detected by positive values of the angular velocity and then the foot contact was detected by the large peak value of the acceleration signal. After detecting the foot contact of the first step, electrical stimulation was applied by detecting the heel off as the large peak acceleration. The angular velocity was monitored during the swing phase and electrical stimulation was stopped by detecting the foot contact from the acceleration signal.

Inclination angles of the segments were calculated using Kalman filter from the data obtained by the wireless inertial sensors [9]. Joint angles were calculated from the inclination angles of the segments. Fig. 2 shows definition of 0 *deg*, and positive and negative values of the inclination and joint angles.

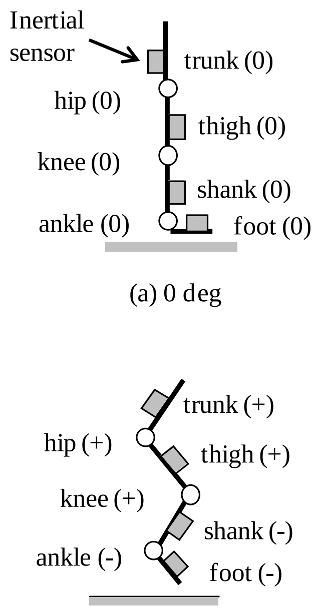
B. Experimental Method

Measurement and control was performed with a right hemiplegic subject (male, 58 years old). The informed consent was gotten from the subject before the measurement.

Electrical stimulation was applied to the common peroneal nerve (CPN) and the tibialis anterior (TA) through a pair of surface electrodes (SRH5080, Sekisui Plastics Co., Ltd.) using biphasic pulses with constant pulse width (0.3 *ms*) and frequency (20 *Hz*). Although pulse amplitude was determined as the value that could develop enough ankle dorsiflexion, 2 stimulation intensities were used in measurement: the submaximam dorsiflexion and the maximum one.

The sensors were attached with the stretchable band, in which the sensors for the thighs and the lumber region were attached on the clothes, and those for the shanks and the feet were on the skin. The measurements were performed without shoes in order to check the foot and finger movements during walking.

First, sitting position at 90 deg of the ankle joint angle, standing positions with knee extension and upright position were measured for angle calibration. Then, gait measurements in 10 *m* walking with and without FES assisted foot drop correction were performed. The subject walked with a quad-point cane left side. In the first 2 trials, the subject walked without electrical stimulation. Then, 2 trials of walking with electrical stimulation (submaximum condition) were measured. After that, the subject walked with FES and effort of dorsiflexion during electrical stimulation (submaximum condition). The 6 trials were repeated twice. Then, the same measurements of 12 trials were performed with increased stimulation intensity (maximum condition) to produce more muscle force by electrical stimulation.



(b) angle direction in movement

Fig. 2. Definition of inclination and joint angles: 0 deg of the angles (a) and positive and negative values of the angles (b) are shown.

III. Results

Examples of measured angles with and without electrical stimulation were shown in Fig. 3 Characteristic angle patterns were found in the measured angles without FES (Fig. 3 (a)). First, hip joint angle range of the paralyzed side was smaller than that of the non-paralyzed side. Knee joint angle pattern of the paralyzed side was significantly different from the non-paralyzed side. That is, in the paralyzed side, the maximum knee flexion angle was small and the knee joint angle showed the second large flexion just after the foot contact because of weakened knee extensor muscles. The ankle joint angle pattern of the paralyze side was also different from the non-paralyzed sides, in which the angle of the paralyzed side was almost negative (plantar flexion) during walking. The shank inclination angle of the paralyzed side largely decreased and increased after the foot contact (around the positive peak), which shows rapid forward and backward movement of the shank. The foot inclination angle showed that the angles of both sides were almost negative during walking and the foot contacted to the floor with the toe, even in the non-paralyzed side. FES assisted walking increased ankle dorsiflexion and foot inclination angle of the paralyzed side during swing phase as seen in Fig. 3(b). It was seemed that the hip joint angle range of the paralyzed side increased.

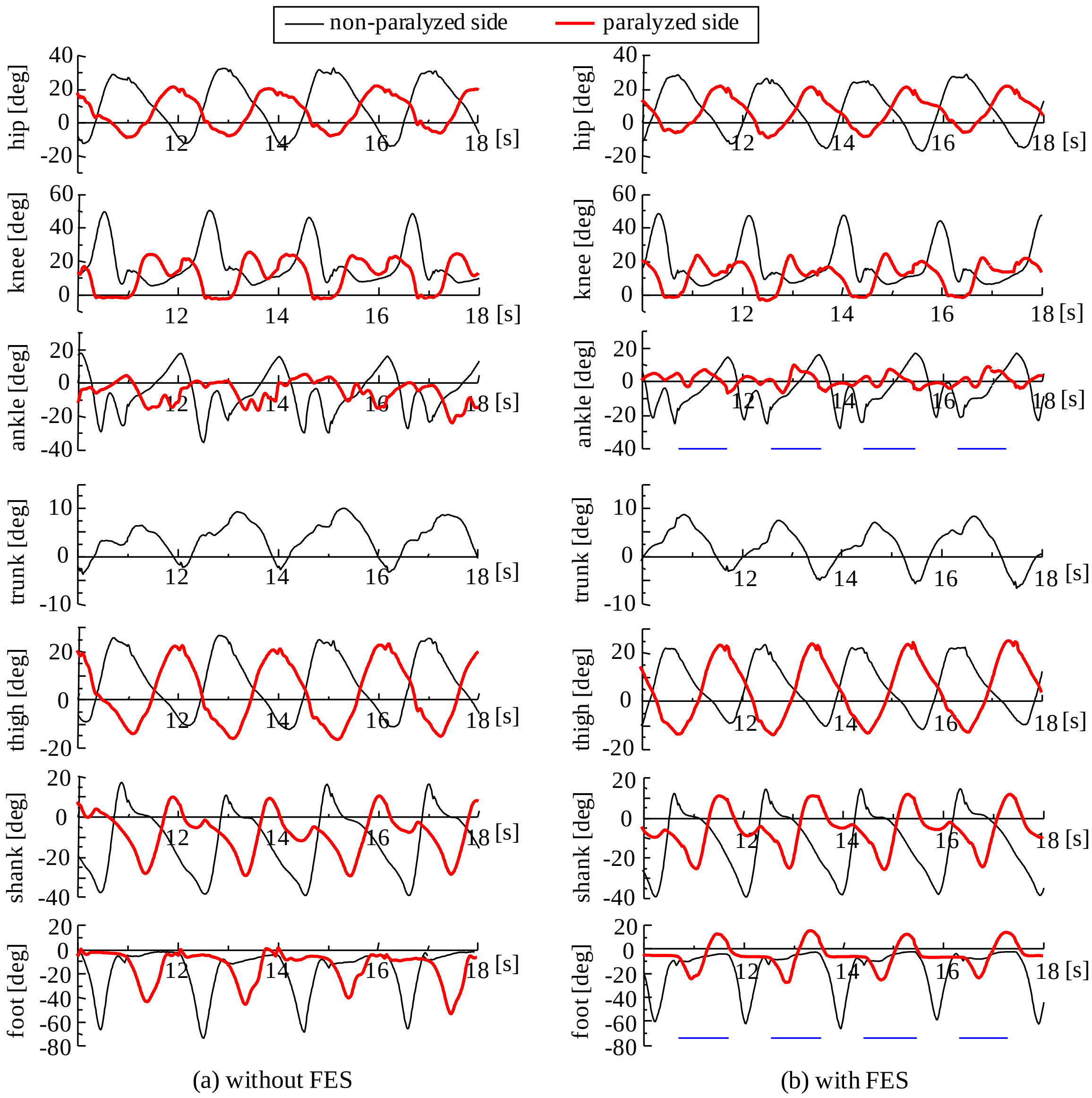


Fig. 3. Examples of measured joint and inclination angles during walking with and without FES assisted foot drop correction (maximum condition). For the FES assisted walking, durations that electrical stimulation was applied are shown by solid lines under the plot.

The joint and inclination angles at the toe off (TO) timing, at the maximum angle point in the swing phase and at the foot contact (FC) timing in the measurement with submaximum condition are shown in Fig. 4. At the TO timing, there were tendencies of increasing of both ankle joint angles and foot inclination angles, and decreasing of knee joint angle of the paralyzed side by using FES control. In the swing phase, the maximum ankle dorsiflexion angle and the maximum foot inclination angle of the paralyzed side increased with electrical stimulation. There were tendencies that the maximum knee flexion angle of the paralyzed side decreased, and the maximum hip flexion angle, the thigh inclination angle increased in the paralyzed side and the thigh inclination angle of the non-paralyzed side decreased. At the FC timing, the hip flexion angle and inclination angles of the shank and the thigh of the paralyzed side had a tendency to increase with FES.

Although most of angles were not different between with and without the voluntary effort, the foot and the shank inclination angles of the paralyzed side at the TO showed small change with the voluntary effort. Variations (standard deviation) of the shank inclination angles of the paralyzed side increased at the TO timing, at maximum angle point in the swing phase and at the FC timing. The variation of the thigh inclination angle of the paralyzed side increased at the maximum angle point in the swing phase and at the FC timing. At the maximum angle point, variation of the foot inclination angle also increased.

Fig. 5 shows inclination angles obtained with larger stimulation intensity (supramaximum condition). It is found that larger stimulation intensity developed larger movement of the foot of the paralyzed side in comparison to those in Fig. 4. However, there were no differences in angles between with and without the voluntary effort. Furthermore, variations of the angles were almost same between with and without the effort.

IV. Discussions

From the measurements with the hemiplegic subject, characteristic angle patterns and change in angles with FES were found. The measurement of all the joint angles and inclination angles were effective for evaluating movements during FES assisted drop foot correction. As expected, the measurement results showed that the FES control performed appropriately in the foot drop correction during the walking. More significantly, however, the measured data did not only show the change in ankle joint angles, but also showed change in inclination angle of the foot and suggested the changes in hip and knee joint angles and inclination angles of the shank and the thigh. Those changes were also caused by the voluntary effort of dorsiflexion.

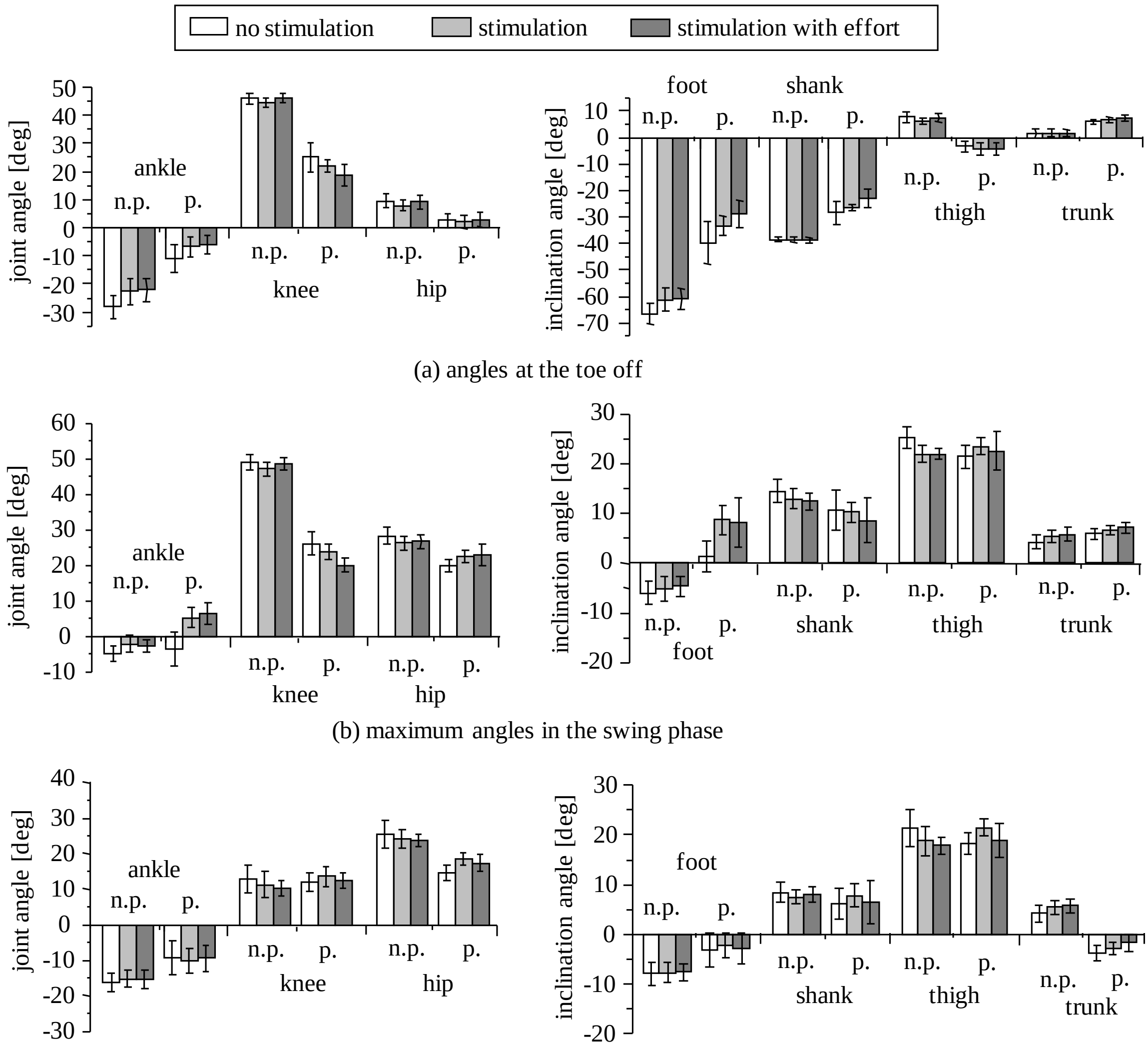


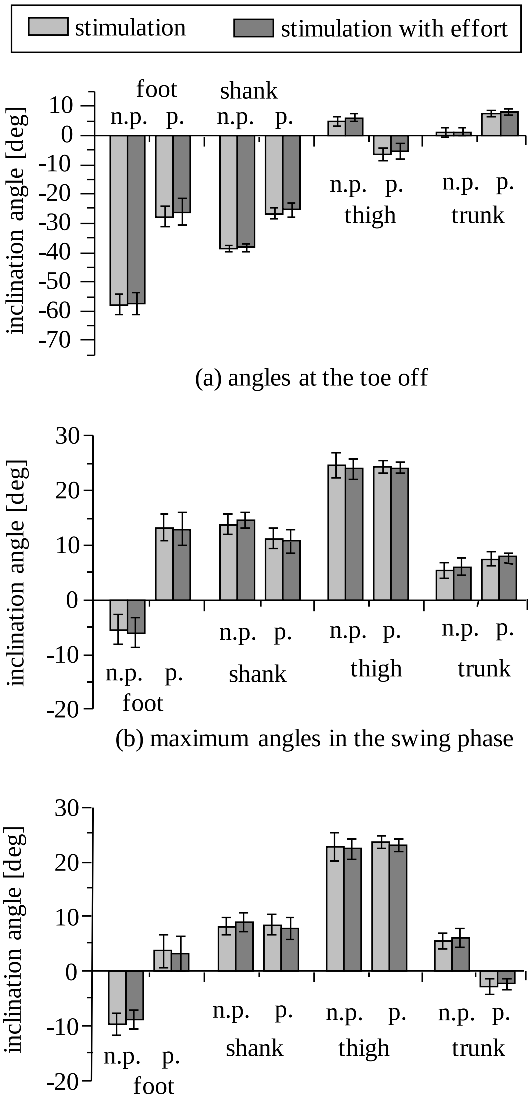
Fig. 4. Joint and inclination angles at the toe off (TO) timing, at the maximum angle point in the swing phase and at the foot contact timing (FC) obtained from the measured data with the hemiplegic subject (submaximum condition). "n.p." and "p." shows the non-paralyzed and the paralyzed sides, respectively.

The foot and the shank inclination angles at the TO timing showed small change with the voluntary effort of dorsiflexion during FES control. In addition, variations of the inclination angles of the foot, the shank and the thigh became large at the TO, at the maximum angle point in the swing phase or at the FC in the case of the voluntary effort. These results suggested that voluntary effort could change movement in FES control. As seen in Fig.5, however, differences in angles and in standard deviations were not shown with larger stimulation intensity (maximum condition). It is considered that movement changes by the voluntary effort were small because the subject could not produce further voluntary muscle force in excess of the muscle force production by FES.

It is considered that movement changes caused by voluntary effort have to be evaluated in rehabilitation training. Although sufficiently-large stimulation intensity can support movements in the training, changes of movement by the voluntary effort are not measured. It would be necessary to determine appropriate intensity of electrical stimulation for rehabilitation use.

V. Conclusion

Gait movements of a hemiplegic subject during FES assisted foot drop correction were measured with the integrated wireless system of movement measurement and FES control. The measurement results showed characteristic angle patterns of hemiplegic gait and effects of FES control. It was also suggested that various angles were changed by applying electrical stimulation for ankle dorsiflexion during swing phase, which means importance of measurement of all the inclination and joint angles in FES control. Voluntary dorsiflexion during FES control was suggested to be able to change movement under the submaximum condition, although changes of movement did not found in measured angles under the maximum condition. In order to use FES in rehabilitation, appropriate stimulation intensity has to be determined considering drawing out voluntary effort of muscle force production.



(a) angles at the toe off

(b) maximum angles in the swing phase

(c) angles at the foot contact

Fig. 5. Inclination angles at the TO, at the maximum angle point in the swing phase and at the FC obtained from the measured data with larger stimulation intensity (maximum condition). "n.p." and "p." shows the non-paralyzed and the paralyzed sides, respectively.

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