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# Clinical Application of Acceleration Sensor to Detect the Swing Phase of Stroke Gait in Functional Electrical Stimulation

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SHIMADA, Y., ANDO, S., MATSUNAGA, T., MISAWA, A., AIZAWA, T., SHIRAHATA, T. and ITOI, E. *Clinical Application of Acceleration Sensor to Detect the Swing Phase of Stroke Gait in Functional Electrical Stimulation.* Tohoku J. Exp. Med., 2005, **207** (3), 197-202 ── Functional electrical stimulation (FES) can improve the gait of stroke patients by stimulating the peroneal nerve in the swing phase of the affected leg, causing dorsiflexion of the foot that allows the toes to clear the ground. A sensor can trigger the electrical stimulation automatically during the stroke gait. We previously used a heel sensor system, which detects the contact pressure of the heel, in FES to correct foot drop gait. However, the heel sensor has disadvantages in cosmetics and durability. Therefore, we have replaced the heel sensor with an acceleration sensor that can detect the swing phase based on the acceleration speed of the affected leg, using a machine learning technique (Neural Network). We have used a signal for heel contact in a gait using the heel sensor before training with the Neural Network. The accuracy of the Neural Network detector was compared with a swing phase detector based on the heel sensor. The Neural Network detector was able to detect similarly the swing phase in the heel sensor. The largest difference in timing of the swing phase was less than 60 milliseconds in normal subjects and 80 milliseconds in stroke patients. We were able to correct foot drop gait using FES with an acceleration sensor and Neural Network detector. The present results indicate that an acceleration sensor positioned on the thigh, which is cosmetically preferable to systems in which the sensor is farther from the entry point of the electrodes, is useful for correction of stroke gait using FES. ──── functional electrical stimulation; hemiplegia; foot drop; sensor; Neural Network



Recent advances in computer technology have made it possible to control paralyzed muscles by electrical stimulation. Since 1990, we have used functional electrical stimulation (FES) with percutaneous intramuscular electrodes to repair paralyzed muscles (Shimada et al. 1996a, b, 2001, 2003). FES has been used to correct the gait of stroke patients. The most common method

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of muscle control by FES uses foot switches, as originally proposed by Liberson. However, that method requires wires or telemetry to connect the switch to the stimulator (Liberson et al. 1961; Jeglic et al. 1971).

To prevent foot drop gait, which is caused by stroke, we have been using percutaneous intramuscular FES with footswitches placed under the heel, as in the Akita Heel Sensor System (AHSS) invented in 1996 (Konishi et al. 1996). The AHSS makes percutaneous intramuscular FES easier to use than previous gait correction systems. Placing a heel sensor in the heel brace helps patients use the system unassisted when walking in Japanese-style rooms. Although the AHSS is useful for treatment of patients with foot drop, there is room for improvement in areas such as cosmetics, durability and ease of installing the system on patients' heels.

To improve the heel sensor, a variety of sensors have been used in studies of correction of foot drop gait. In 1996, Dai et al. (1996) reported that the tilt sensor must be positioned on the calf, in order to prevent foot drop gait during FES. A miniature stimulator for foot drop has been designed with a magnetoresistive tilt sensor built in; no external sensor cables are required, but a tilt sensor on the calf is still required. The available evidence suggests that if the acceleration sensor is put on the thigh (i.e., nearer the entry point of the electrodes on the thigh), it will improve the ability to detect steps during gait. Patients can also put the sensors on more easily by themselves using the above-described system. We previously measured foot drop gait cycles using a tilt sensor positioned on the anterior part of the thigh (Ando et al. 1999). We were able to detect the beginning of the swing phase using that system. However, the tilt sensor tended to detect gait cycles later than the control, which measured gait cycles using the automatic coordination system. To detect foot drop gait cycles more accurately, the rule induction algorithm was introduced to adapt the stimulation to foot drop gait. Kostov et al. (1999) used Adaptive Logic Networks (ALN) to design a stance swing detector for FES control of hemiplegic gait. To detect the swing phase in foot drop gait, we recently developed a Neural Network and an acceleration sensor designed to be positioned on the thigh.

The purpose of this study was to evaluate the possibility of detecting normal and foot drop gait cycles using a 2-axis accelerometer positioned on the anterior part of the thigh.

## Materials and Methods

The subjects were 5 healthy males and 3 stroke patients. The average age was 30 years (range, 23-44 years) and 67 years (range, 57-72 years), respectively. For all 3 stroke patients, functional classification of stroke was Brunnstrom V. Written informed consent was obtained from all 8 subjects.

One 2-axis accelerometer (ADXL 202: Analog Devices, Inc., Tokyo) was used in this study (Fig. 1). The acceleration sensor, which can measure changes in acceleration in two axes, was mounted on the ADXL 202 evaluation board and positioned on one side of the lateral middle part of the thigh. We measured changes in acceleration during gait in the sagittal and gravitational directions of the thigh. The gain of the onboard amplifier was set at 2, giving a range of ± 2 g. The signals were recorded using a ND-2000 recorder (KEYENCE, Inc., Osaka), at a sampling rate of 100 Hz. The heel sensor's force-sensing resistors (Click BPG, Tokyo Sensor, Inc., Tokyo) were placed under the heel on the same side as

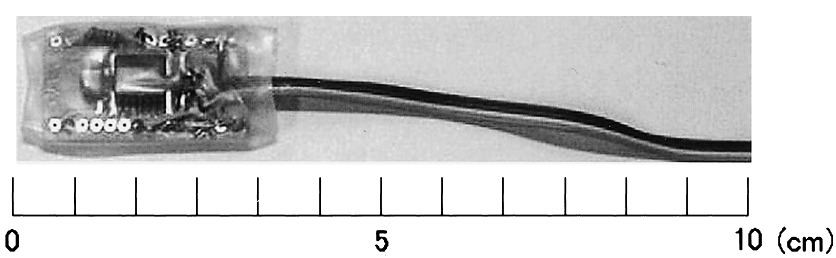


Fig. 1. Acceleration sensor (ADXL202).

the sensor, to provide reference points for the step cycle.

An acceleration sensor was positioned on the lateral middle part of the thigh (Fig. 2). We measured acceleration of the thigh during gait using the acceleration sensor, and simultaneously measured the timing of heel contact during gait using a heel sensor. The heel sensor was placed under the heel to provide reference points for the step cycle. Subjects walked barefoot on the laboratory floor. Gait speed was normal. For each data record, the numbers of gait cycles was greater than 50.

The data was input into a personal computer, and was processed using a learning form. For Neural Network training, the acceleration data was processed with the input data, and the heel data was processed with the target data. We calculated bias and weight of the Neural Network using MATLAB (Cybernet System, Inc., Tokyo) and the Neural Network Toolbox (The MathWorks, Inc., Natick, MA, USA). We wrote a Neural Network program including weight and bias, using the computer programming language C, and forwarded the program to a microcomputer. The microcomputer produced output signals for stimulation in swing phase using the Neural Network program, in real time. The accuracy of the microcomputer output data was compared with the output data using the heel sensor.

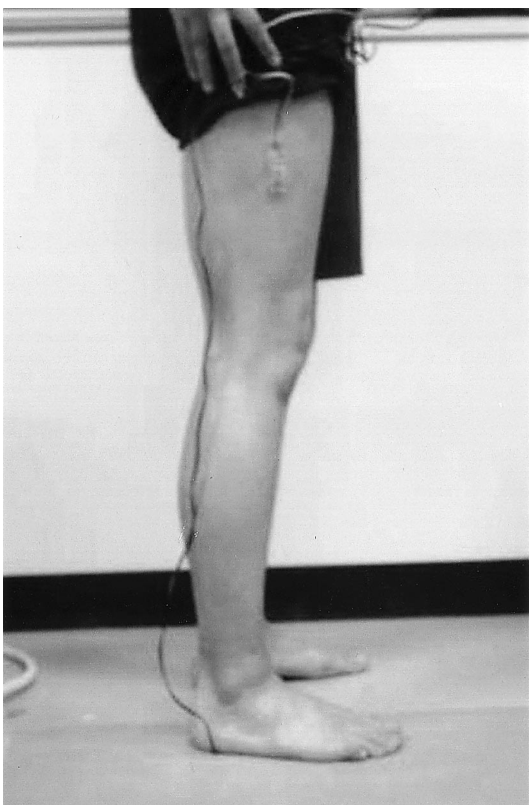

Fig. 2. Acceleration sensor positioned on the thigh.

Stroke patients walked on the laboratory floor, and the acceleration change of the thigh was measured during gait. Using the Neural Network program, acceleration data was processed into output data in real time. The microcomputer was connected to the stimulator, and the output data was used to control electrical stimulation. Force-sensing resistors measured heel contact and heel-off simultaneously. The accuracy of the microcomputer output data was compared with the accuracy of the output data of the heel sensor.

## RESULTS

In normal subjects, the Neural Network detector was able to detect the swing phase in the gait cycle, which is similar to what the heel sensor detected (Fig. 3 and 4). The maximum difference in the timing of the swing phase was less than 60 milliseconds.

In stroke patients, the Neural Network detector was also able to detect the swing phase in the gait cycle. Some of the control signals obtained contained sporadic stimulation spikes in the stance phase (Fig. 5). The maximum difference in the timing of the swing phase was less than 80 milliseconds.

The output data was used for FES to correct foot drop gait. The Neural Network detector was able to detect the swing phase, and the stimulator was able to stimulate in the swing phase during gait. We were able to correct foot drop gait using the acceleration sensor, Neural Network detector and FES.

## DISCUSSION

A variety of artificial and natural sensors have been studied for use in FES of feet, including gyroscopes (Ghoussayni et al. 2004), tilt sensors (Dai et al. 1996), electronystagmographic signals (Hansen et al. 2004), electromyographic signals (Vodovnik et al. 1965), and accelerometers (Mansfield and Lyons 2003). Ghoussayni et al. (2004) reported that overall accuracy of the gyroscope sensor system when worn on the shank was 96% for able-bodied subjects and 94% for stroke patients. However, there are cosmetic problems

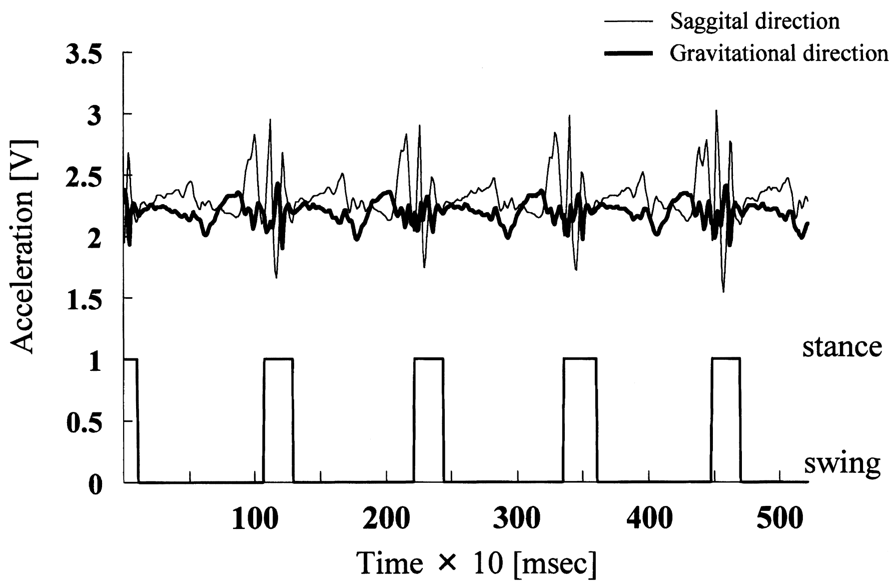


Fig. 3. Acceleration changes of the thigh in a healthy subject.
The bold line indicates changes in gravitational direction, and the fine line indicates changes in sagittal direction. The lower line shows the step cycles, stance and swing phase.

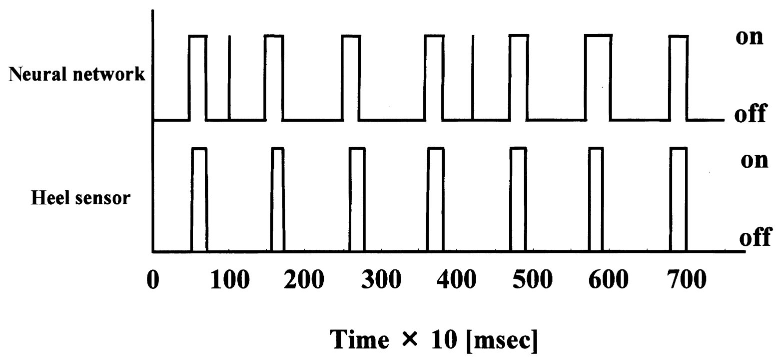


Fig. 4. Output signals in a healthy subject.
The upper line indicates output signals of the Neural Network. The lower line indicates the heel sensor output signals, which are considered the correction of the gait cycle. The Neural Network detected the swing phase of the gait cycle, which is similar to what the heel sensor detected.

with the gyroscope sensor worn on the shank. The present system, in which an acceleration sensor is positioned on the thigh, is cosmetically preferable to systems in which the sensor is farther from the entry point of the electrodes.

The accuracy of a sensor system is the most important factor in its clinical application with paralytic patients. Systems that use only a gyroscope or acceleration sensor have limited accuracy. The present system uses a Neural Network to reduce the maximum difference in timing of the swing phase. We were able to detect the swing phase using only the Neural Network and an acceleration sensor. In the gait of normal subjects, the maximum difference in the timing of the swing phase was less than 60 milliseconds. The differences in timing were less than 5% during the swing phase, and were considered negligible for the overall performance of the system for correction of foot drop. In the present study, we mea-

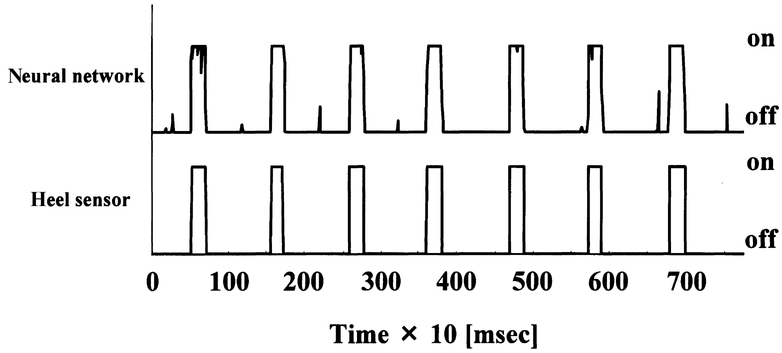


Fig. 5. Output signals in a stroke patient.
The upper line indicates output signals of the Neural Network. The lower line indicates the heel sensor output signals, which are considered the correction of the gait cycle. The Neural Network detected the swing phase of the gait cycle.

sured the gait of stroke patients, which involved foot drop and circumduction. differences the timing of events in the gait of stroke patients and the timing of events in normal gait, including length of the swing phase, angular changes of the hip and knee joint, and acceleration changes of the thigh on the affected side. We measured foot drop gait cycles using a tilt sensor positioned on the anterior part of the thigh. The beginning of the swing phase was detected. However, the tilt sensor tended to detect gait cycles later than the control, which measured gait cycles using the automatic coordination system. Use of a tilt sensor positioned on the thigh does not facilitate detection of phases of the hemiplegic gait cycle (Ando et al. 1999). Despite these differences, the Neural Network detector detected the swing phase of stroke patients with a sensitivity similar to that for normal subjects. This suggests that an acceleration sensor, which was positioned on the affected-side thigh in the present study, can also be used in a heel sensor system. The Neural Network detector can thus correspondingly predict the beginning of gait events. We believe that the present acceleration sensor system can reduce the time required for attaching and removing sensors, improve ease of use by patients, improve cosmetic appearance, provide accurate and reliable triggering sensors, provide sufficient information for establishment of feedback control, be modified for miniaturization and implantation, and overcome several limitations of foot switches.

## Conclusion

An acceleration sensor positioned on the thigh can be used to measure gait cycle. The present findings suggest that positioning an acceleration sensor on a stroke patient's thigh improves the results of FES for correction of gait in stroke patients.

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