GAIT CYCLE DETECTION USING A TRI-AXIAL ACCELEROMETER AND A GYROSCOPE IN HEMIPLEGIC PATIENTS : A PRELIMINARY REPORT

Takenori Tomite[1)], Yoichi Shimada[1)], Toshiki Matsunaga[2)], Kana Sasaki[1)], Takayuki Yoshikawa[1)] and Takehiro Iwami[3)]

(received 13 December 2011, accepted 28 December 2011)

[1)]*Department of Orthopedic Surgery, Akita University Graduate School of Medicine, Akita 010-8543, Japan*
[2)]*Department of Rehabilitation Medicine, Akita University Hospital, Akita 010-8543, Japan*
[3)]*Department of Mechanical Engineering, Akita University Faculty of Engineering and Resource Science, Akita 010-8502, Japan*

Abstract
Objective : To evaluate the capability for gait cycle detection using a tri-axial accelerometer and gyroscope in hemiplegic patients.
Materials & Methods : Twenty hemiplegic patients participated in this study. The sensors were placed on the tibial tubercle of the affected knee. We divided the patients into groups according to Brunnstrom stage to evaluate whether the sensors can detect gait cycle irrespective of the degree of paralysis. To evaluate whether errors and delay times seen in signals of the sensors were too pronounced for a hemiplegic patient's gait, we asked 5 hemiplegic patients, who had errors and delay times, to walk with functional electrical stimulation (FES) from signals of only the sensors and compared walking speed and step cadences for walking with and without stimulation.
Result : Outputs of the sensor signals had some errors and were behind the output of heel sensor signals. The total number of steps was 912. The total number of errors was 20 (2.0%). Average delay time was 0.058 sec ($N=20$). There were no significant differences among Brunnstrom stages in terms of appearances of errors and average delay times ($p>0.05$; Kruskal-Wallis rank-sum test). Five patients who were asked to walk with FES from signals of the sensors had faster walking speed and fewer steps than when walking without FES ($p<0.05$; Wilcoxon signed rank test).
Conclusion : Although errors and delay times were observed in the output of the sensor signals, patients who were asked to walk with FES from the sensor signals could obtain a better walking ability.

Key words : functional electrical stimulation (FES), gait cycle detection, hemiplegia, accelerometer

Introduction

After stroke or traumatic brain injury, hemiplegic patients often suffer from foot drop. An ankle-foot orthosis (AFO), which maintains the foot in a neutral position to prevent it from dragging during the swing phase of gait, has been used to manage foot drop[1)]. Another approach to the management of foot drop is a functional

Correspondence : Takenori Tomite
Department of Orthopedic Surgery, Akita University Graduate School of Medicine, 1-1-1 Hondo, Akita 010-8543, Japan
Tel : 81-18-884-6148
Fax : 81-18-884-2617
E-mail : tomite@doc.med.akita-u.ac.jp

electrical stimulation (FES) system, which can provide active gait correction.

In 1961, Liberson *et al*. were the first to use FES to correct foot drop in hemiplegic patients. They stimulated the peroneal nerve electrically via electrodes attached to the skin at the head of the fibula and used a stimulator controlled by a switch in the heel of the shoe on the affected foot[2]. Since its introduction, FES for correction of foot drop has been studied[3-7]. We have also used an FES system with a heel sensor to correct foot drop[8].

Although some researchers have recently reported gait cycle detection using an accelerometer instead of a heel sensor and succeeded in detecting gait cycle[9-14], practical applications of FES using accelerometers for hemiplegic patients have not been reported. Recent studies have been reported on an alternative gait cycle detection system involving a heel sensor. Jasiewicz *et al*. reported on gait cycle detection using a tilt sensor placed on the knee and the foot, and using an accelerometer placed on the foot[11]. Shimada *et al*. reported gait cycle detection using a tilt sensor placed on the lateral thigh, and using an accelerometer placed on the lateral thigh[14]. They reported that a tilt sensor was not suitable for gait cycle detection of hemiplegic patients but an accelerometer did enable such gait detection. By placing an accelerometer and a gyroscope on the tibial tubercle of the affected knee, we consider that we can detect gait cycle and stimulate the peroneal nerve at the same time and at a single site without the need for shoes to be worn. We carried out FES by using the signals of a tri-axial accelerometer and a gyroscope for hemiplegic patients and inspected whether errors of a tri-axial accelerometer and a gyroscope have a detrimental influence on the gait of hemiplegic patients.

The purpose of this study is to evaluate whether a tri-axial accelerometer and a gyroscope mounted on the knee can detect the gait cycle of hemiplegic patients and can improve the gait of hemiplegic patients without having a detrimental influence.

Methods

Subjects

Twenty hemiplegic patients (14 males, 6 females) participated in this study. They have suffered chronic stroke (more than 6 months having passed since the onset), and could walk by themselves using walking assistance tools and AFO. The average age was 66 years old (range, 41-84 years). We classified them in terms of the Brunnstrom stage. The numbers in each stage were as follows : Stage 3 : 5 patients, Stage 4 : 5 patients, Stage 5 : 7 patients, and Stage 6 : 3 patients. They were asked to walk at least 30 m at their normal self-selected pace on a flat floor. They were permitted to use tools to assist in walking and AFO. The local ethical committee approved the study and all subjects participating in the study provided informed consent.

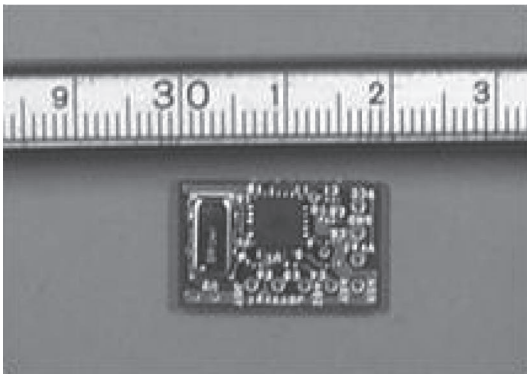

Fig. 1. A tri-axial accelerometer and a gyroscope fixed on one base (2.0×1.4 cm).

Devices

A tri-axial accelerometer (Hitachi Metals H48D, 4.8×4.8×1.5 mm) and a gyroscope (Murata ENC-03R, 4.0×8.0×2.0 mm) were fixed on one base (2.0×1.4 cm) and were fixed on the tibial tubercle of the affected knee using a belt (Fig. 1). A heel sensor was placed on the affected sole as a control signal (Click BP, Tokyo Sensor Co., 35×17×4 mm). We asked patients to walk (first walk) and collected signals from the accelerometer, the gyroscope and the heel sensor. The collected signals were sent to a data logger (Hioki 8430 Memory Hilogger) by wire online. A data logger recorded these signals every 10 msec.

Protocol

The signals recorded in the data logger were trans-

ferred to a computer via an SD card for processing using Neural Network Learning (MATLAB Neural Network Toolbox). The use of Neural Network Learning (NNL) enables detection of gait cycle by using only a tri-axial accelerometer and a gyroscope by means of converting their signals into signals showing swing and stance phases, like the signals of a heel sensor. After establishing NNL, we asked patients to walk (second walk), with data processed by NNL, and collected data again. NNL training was performed for each subject separately : in other words, signals were recorded and the results of NNL were rewritten one by one.

The data obtained from the second walk were compared with the data obtained from the heel sensor, which was used to provide a control signal. We converted the data into a graph and counted the number of errors. If the graph signals of NNL were different from the graph signals of the heel sensor, this was counted as an error. In addition, delay times were observed in the output of the tri-axial accelerometer and the gyroscope compared with the output of the heel sensor. We measured the duration of the delay times.

To investigate whether errors and delay times seen with the tri-axial accelerometer and the gyroscope were too pronounced for a hemiplegic patient's gait, 5 patients who had errors and delay times were asked to walk with FES and without FES from only tri-axial accelerometer and gyroscope signals on a 10-m course. We compared walking speed and steps of hemiplegic patients. The Brunnstrom stages of these 5 patients were as follows : Stage 3 : 2 patients, Stage 4 : 2 patients, and Stage 5 : 1 patient. Selected patients were those who did not require AFO for their walking.

For walking with FES, the sensors were placed on the tibial tubercle of the affected knee again and we stimulated tibialis anterior and peroneal nerve using surface electrode (Pulsecure Pro®). We compared walking speed and steps with FES and without FES. Requirements for FES walking were data studied by NNL, surface electrode, and converter (total size 7×10×3 cm).

Results

Twenty patients completed the program. We compared the signals of the accelerometer and gyroscope with the signals of the heel sensor. Typical graph exam-

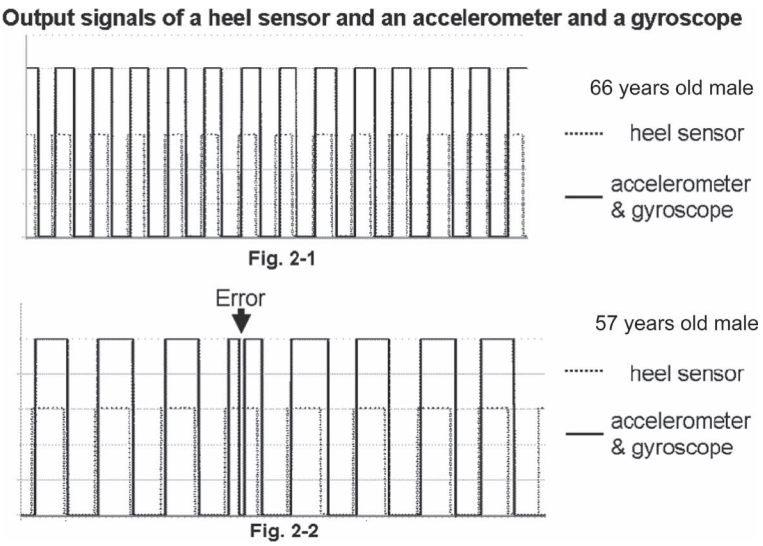

Fig. 2. The solid line shows heel sensor signals. The dotted line shows tri-axial accelerometer and gyroscope signals processed by NNL. We can see that the line representing signals of an accelerometer and a gyroscope follows the line representing signals of a heel sensor in Fig. 2-1. The arrow in Fig. 2-2 shows an error. We can see different signals between the line representing an accelerometer and a gyroscope and the line representing a heel sensor.

Table. The ratio of the error detection with regard to Brunnstrom Stage

Brunnstrom Stage	3	4	5	6
Steps	212	231	328	141
errors	6	7	7	0
Average (%)	1.59	3.53	1.93	0

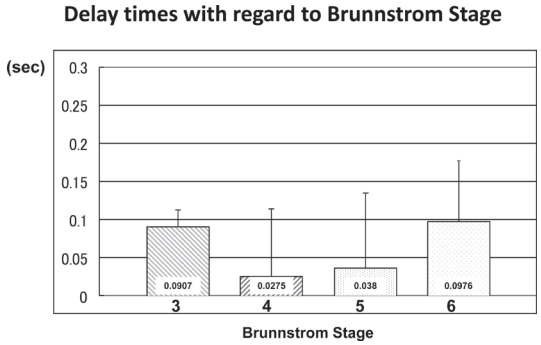

Fig. 3. This graph shows delay times appearing in signals from an accelerometer and a gyroscope with regard to Brunnstrom stage. No significant difference in delay times was found among Brunnstrom stage groups ($p>0.05$, Kruskal-Wallis rank-sum test).

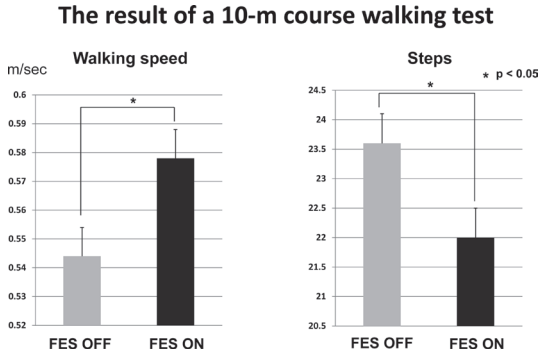

Fig. 4. The left graph shows walking speed (m/sec) of 5 patients with FES from signals of the sensors and without FES (barefoot). The average walking speed was 0.544 m/sec in cases without FES and 0.578 m/sec in cases using FES. The right graph shows number of walking steps of 5 patients with FES from signals of the sensors and without FES (barefoot). The average number of walking steps was 23.6 in cases without FES and 22.0 in cases using FES. Patients who were given FES could walk faster and take fewer steps than those with barefoot ($p<0.05$; Wilcoxon signed rank test).

ples are shown in Fig. 2-1 and 2-2 (Fig. 2-1 is a good pattern and Fig. 2-2 is a failed (appearing errors) pattern). If the signals of the tri-axial accelerometer and gyroscope did not follow the signals of the heel sensor, it was counted as an error. The total number of calculated steps was 912.

The total number of errors was 20 (2.2% of total steps). Thirteen patients did not have any errors and 7 patients had 20 errors. With regard to the Brunnstrom stage, the numbers of steps in each stage were as follows : Stage 3 : 212, Stage 4 : 231, Stage 5 : 328, and Stage 6 : 141, and the percentages of errors were as follows : Stage 3 : 1.59%, Stage 4 : 3.53%, Stage 5 : 1.93%, and Stage 6 : 0% (Table). There were no significant differences among Brunnstrom stages in terms of the appearance of errors ($p>0.05$; Kruskal-Wallis rank-sum test). This means that the utility of the tri-axial accelerometer and the gyroscope was not affected by the degree of paralysis.

Outputs of the tri-axial accelerometer and the gyroscope signals were behind the outputs of heel sensor signals. The average delay time was 0.058 sec ($N=20$). With regard to the Brunnstrom stage, average delay times were as follows : Stage 3 : 0.0907 sec, Stage 4 : 0.0275 sec, Stage 5 : 0.038 sec, and Stage 6 : 0.0976 (Fig. 3). There were no significant differences among Brunnstrom stages in terms of average delay time ($p>0.05$; Kruskal-Wallis rank-sum test).

To investigate whether the errors and delay times seen with the tri-axial accelerometer and the gyroscope were too pronounced for a hemiplegic patient's gait, 5 patients who had errors and delays were asked to walk with FES and without FES from only tri-axial accelerometer and gyroscope signals on a 10-m course. All patients selected for a 10-m course test were the patients who did not have to equip AFO, and all patients were compared their walking speed and steps in their bare foot with those in FES. Patients with FES from signals of only the tri-axial accelerometer and gyroscope had faster walking speed and fewer steps than patients without FES ($p<0.05$; Wilcoxon signed ranks test) and they did not stumble (Fig. 4).

Discussion

A heel sensor has generally been used to detect gait cycle. However, some faults with heel sensors have been discussed. A heel sensor that is used on a daily basis has problems with durability and a long electric wire is needed to connect the heel sensor to the stimulator. Recently, FES system using a heel sensor without an electric wire has been developed[15]. However, a heel sensor is not suitable for the Japanese lifestyle where one needs to take off their shoes[16] and a sensor and a stimulator had to be set up on separate place. If we can detect gait cycle near stimulation point, the detection of gait cycle and the stimulation of muscle and nerve will be possible at one place and FES device may be able to be smaller.

In this study, we used NNL to analyze gait cycle detection. Kostov *et al*. reported that sensor signals were recorded using a pressure sensor installed in the insoles of a subject's shoes and a goniometer attached across the joints of the affected leg in a subject with spinal cord injured. The machine-learning techniques used were adaptive logic network and inductive learning algorithm[17]. Tong *et al*. reported that neural networks were used to construct FES controllers to control the timing of stimulation. Two subjects with incomplete spinal cord injury were recruited, using different numbers of sensors in the sensor set and different numbers of data points from each sensor. The result showed that the neural network controllers can maintain a high accuracy[18]. Although we used network system similar to theirs, some errors and delay times were observed in this study. Some reasons for these errors can be considered. We used same the sensors throughout this study and put the sensors on the same position by marking to avoid dislocation. And the signals of sensors were sent to a data logger by wire exactly as it was. So there seems to be no possibility of the sensors causing errors. However, the signals were filtered with 10 Hz for recording a data when the signals were sent to a data logger and a data logger recorded these signals every 10 msec. So we expect that the cause of errors is due to processing time of the signals ; filtering of the signals or interval of recording the signals.

A tri-axial accelerometer has been used for gait analysis recently[19,20]. Such studies suggest that accelerometers are reliable for assessment. Although gait analysis using a tri-axial accelerometer has been carried out, clinical validity of using a tri-axial accelerometer and NNL for hemiplegic patients has not been reported. So assuming various margin of errors with using an accelerometer, processing a data, and using NNL have not been evaluated either. We want to compare the influence of errors and delay time for FES walking with a conventional device. However literatures of evaluating delay time and clinical assessment together have not been reported as far as we search.

In the current case, although there were some errors and delay times, there were no significant differences among Brunnstrom stages in terms of average delay times and appearance of errors. In addition, by using FES from the signals of an accelerometer and a gyroscope, the gait ability of hemiplegic patients was improved without any troubles. However, the size of our FES system was relatively big (7 cm×10 cm×3 cm) and honestly, it was not comfortable for hemiplegic patients to use for daily outfit yet. There is a room for improvement in the size of our FES system, We are trying to reduce the size to a minimum. An accelerometer and a gyroscope have potential for the development of compact FES systems.

References

1) Lehmann, J.F., Condon, S.M., Price, R. and deLateur, B.J. (1987) Gait abnormalities in hemiplegia : their correction by ankle-foot-orthoses. *Arcb. Phys. Med. Rehabil.*, **68**, 763-771.

2) Liberson, W., Holmquest, H. and Scott, M. (1961) Functional electroptherapy : stimulation of the common peroneal nerve synchronized with the swing phase of gait of hemiplegic subjects. *Arcb. Phys. Med. Rehabil.*, **42**, 202-205.

3) Waters, R.L., McNeal, D. and Perry, J. (1975) Experimental correction of footdrop by electrical stimulation of the peroneal nerve. *J. Bone. Joint. Surg.*, **57A**, 1047-1054.

4) Vodovnik, L., Kralj, A., Stanic, U., Acimovic, R. and Gros, N. (1978) Recent applications of functional

electrical stimulation to stroke patients in Ljubljana. *Clin. Orthop.*, **131**, 64–70.

5) Upshaw, B.J. and Sinkær, T. (1997) Natural versus artificial sensor applied in peroneal nerve stimulation. *Artif. Organs*, **21**, 227–231.

6) Taylor, P.N., Burridge, J.H., Dunkerley, A.L., *et al*. (1999) Clinical use of the Odstock dropped foot stimulator : its effect on the speed and effort of walking. *Arcb. Phys. Med. Rehabil.*, **80**, 1577–1583.

7) Brandell, B.R. (1982) Development of a universal control unit for functional electrical stimulation. *Am. J. Phys. Med.*, **61**(6), 401–405.

8) Shimada, Y., Sato, K., Kagaya, H., Konishi, N., Miyamoto, S. and Matsunaga, T. (1996) Clinical use of percutaneous intramuscular electrodes for functional electrical stimulation. *Arcb. Phys. Med. Rehabil.*, **77**, 1014–1018.

9) Kavanagh, J.J., Morrison, S., James, D.A. and Barrett, R. (2006) Reliability of segmental accelerations measured using a new wireless gait analysis system. *J. Biomech.*, **39**, 2863–2872.

10) Saremi, K., Marehbian, J., Yan, X., Regnaux, J.P., Elashoff, R., Bussel, B., *et al*. (2006) Reliability and validity of bilateral thigh and foot accelerometry measures of walking in healthy and hemiparetic subjects. *Neurorehabil. Neural. Repair.*, **20**, 297–305.

11) Jasiewicz, J.M., Allum, J.H.J., Middleton, J.W., Barriskill, A., Condie, P., Purcell, B. and Che Tin Li., R. (2006) Gait event detection using linear accelerometers or angular velocity transducers in able-bodied and spinal-cord injured individuals. *Gait. & Posture*, **24**, 502–509.

12) Moe-Nilsson, R. and Helbostad, J.L. (2005) Interstride trunk acceleration variability but not stop width variability can differentiate between fit and frail older adults. *Gait & Posture*, **21**, 164–170.

13) Zijlstra, W. and Hof, A.L. (2003) Assessment of spatiotemporal gait parameters from trunk acceleration during human walking. *Gait & Posture*, **18**, 1–10.

14) Shimada, Y., Ando, S., Matsunaga, T., *et al*. (2005) Clinical application of acceleration sensor to detect the swing phase of stroke gait in functional electrical stimulation. *Tohoku J. Exp. Med.*, **207**, 197–202.

15) van Swingchem, R., Vloothuis, J., den Boer, J., Weerdesteyn, V. and Geurts, A.C. (2010) Is transcutaneous peroneal stimulation beneficial to patients with chronic stroke using an ankle-foot orthosis ? A within-subjects study of patients' satisfaction, walking speed and physical activity level. *J. Rehabil. Med.*, **42**(2), 117–121.

16) Shimada, Y., Matsunaga, T., Misawa, A., Ando, S., Itoi, E. and Konishi, N. (2006) Clinical application of peroneal nerve stimulator system using percutaneous intramuscular electrodes for correction of foot drop in hemiplegic patients. *Neuromodulation*, **9**(4), 320–327.

17) Kostov, A., Andrews, B.J., Popovic, D.B., Stein, R.B. and Armstrong, W.W. (1995) Machine learning in control of functional electrical stimulation systems for locomotion. *IEEE Trans. Biomed. Eng.*, **42**, 541–551.

18) Tong, K.Y. and Granat, M.H. (1999) Reliability of neural-network functional electrical stimulation gait-control system. *Med. Bio. Eng. Comput.*, **37**, 633–638.

19) Hartmann, A., Luzi, S., Murer, K., de Bie, R.A. and de Bruin, E.D. (2009) Concurrent validity of a trunk tri-axial accelerometer system for gait analysis in older adults. *Gait & Posture*, **29**, 444–448.

20) Mizuike, C., Ohgi, S. and Morita, S. (2009) Analysis of stroke patient walking dynamics using a tri-axial accelerometer. *Gait & Posture*, **30**, 60–64.