31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

A Pelvic Motion Driven Electrical Stimulator for Drop-Foot Treatment

Shih-Wei Chen, Shih-Ching Chen, Chiun-Fan Chen, Jin-Shin Lai and Te-Son Kuo

Abstract—**Foot switches operating with force sensitive resistors placed in the shoe sole were considered as an effective way for driving FES assisted walking systems in gait restoration. However, the reliability and durability of the foot switches run down after a certain number of steps. As an alternative for foot switches, a simple, portable, and easy to handle motion driven electrical stimulator (ES) is provided for drop foot treatment. The device is equipped with a single tri-axis accelerometer worn on the pelvis, a commercial dual channel electrical stimulator, and a controller unit. By monitoring the pelvic rotation and acceleration during a walking cycle, the events including heel strike and toe off of each step is thereby predicted by a post-processing neural network model.**

I. Introduction

The most common cause of abnormal gait in subjects suffering from hemiplegia is the drop foot[1]. Patients who are physically challenged from drop foot usually drag their toes in locomotion because they cannot keep them away from the ground during swing phase of a gait cycle. This is mainly caused by improper control of tibialis anterior muscle, which makes a normal ankle dorsi-flexion nearly impossible. Moreover, the risk of falling increases as the toe is dragged during ambulation[2]. The conventional solution for the drop foot is by applying surface functional electrical stimulation (FES) that mimics electrical impulses sent through the central nervous system (CNS). Instead of sending nerve impulses from the motor cortex, the tibialis anterior muscle is stimulated with correct timing to restore the normal gait and to deviate from the abnormal gait induced by the drop foot.

Foot switches that operate with force sensitive resistors placed in the shoe sole has provided a common open loop control scheme for driving the FES assisted walking system for gait restoration since the 1960s[3]. However, foot switches in clinical applications have problems associated with deformation, mechanical breakage of solder joints and sticking of contacts [4]. Specifically, the reliability and durability reduces when the sensor material degrades after use. Furthermore, the heel strike of foot switches may be falsely detected during swing phase or during the shuffling of the feet[5]. Therefore, a time-consuming practice of controlling the FES-assisted system for inexperienced users will be a prerequisite to prevent the incorrect switching actions.

Recent advances in sensors including electronic goniometers, gyroscopes, tilt sensors, and accelerometers have made closed-loop control studies applicable for driving FES assisted walking systems [4, 6-11]. The foregoing substitutes of the foot switches are more reliable, durable, and are also applied for better cosmetic purposes. Nevertheless, all sensors have their limitations. For example, the examiner's experience of attaching the sensors is particularly important in any application.

The accelerometer is a sensor for detecting rapid and sensitive motion with advantages of cost over electronic goniometers, gyroscopes, and tilt sensors. Since the differences in acceleration waveform repeatability associated with the reapplication of accelerometers were small in relation to normal motor variability[12], accelerometers were used in this study. In previous studies, the accelerometers have been placed on the trunk and different segments of the leg to act as alternatives of foot switches [5, 9, 13]. However, these positions may result in muscle synergy when the users have to raise or swing their leg to produce the signals for the predicted motion. In order to minimize muscle synergy when driving the FES assisted walking system, we propose using pelvic rotation as a command for recruiting specific muscle groups.

The pelvic rotation occurs in order to increase the step length for bipedal walking either in normal subjects or in patients with abnormal gait[14]. We should be able to know the gait cycle events through the observation of the periodic pelvic motions because they lead subsequent motions of the swing phase in a single gait cycle[15]. Therefore, we suppose that the gait events including heel strike, flat foot, toe off, and swing phase can be readily predicted by using a single accelerometer when the pelvic motions are properly detected.

In this study, pelvic motion signals of normal subjects were collected and recorded for predicting their gait events. A new

Manuscript received April 23, 2009.

This work was supported in part by the NSC95-2221-E-038-010-MY3 (3-3) and the NSC 97-2221-E-002-218-MY3 (1/3).

Shih-Wei, Chen is with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan (phone: 886-3366-9750; e-mail: r92921115@ ntu.edu.tw).

*Shih-Chen, Chen is with the Department of Physical Medicine and Rehabilitation, Taipei Medical University and Hospital, Taipei, Taiwan (corresponding author, phone: 886-2737-2181; e-mail: csc@tmu.edu.tw).

Chiun-Fan, Chen is with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan (phone: 886-3366-9750; e-mail: cfchen@ntu.edu.tw).

Jin-Shin, Lai is with the Department of Physical Medicine and Rehabilitation, Taipei, National Taiwan University Hospital and Medical College, Taipei, Taiwan (phone: 886-2312-2349; e-mail: jslai@ntu.edu.tw).

Te-Son, Kuo is with the Department of Electrical Engineering, Institute of Biomedical Engineering, Graduate Institute of Biomedical Electronics and Bioinformatics, National Taiwan University, Taipei, Taiwan (phone: 886-3366-3632; e-mail: kuo@ntu.edu.tw).

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

design of FES system for drop-foot treatment was proposed.

II. Materials and Methods

A. Experimental Setup

In preliminary experiments, we recruited 3 healthy male subjects as volunteers (subject A: 182cm, 76kg, 29 y/o; subject B: 181cm, 80kg, 28 y/o; subject C: 172cm, 73kg, 29y/o). These subjects have had no history of musculoskeletal impairment, neurological disorder, cardiac or other pulmonary pathologies, and they are well conscious of the experimental instructions.

One accelerometer was soldered on a compact printed circuit board (PCB). 10Hz capacitor filters were applied to the accelerometer signal for prior sampling. The PCB was attached to the subject's anterior superior iliac spine (ASIS) on the right side of the pelvis by using tape and velcro straps for secure fastening. The accelerometer was used to measure the accelerations in vertical (VT), anterior-posterior (AP), and medial-lateral (ML) axes in walking for predicting the gait events. Generally, the foot switch is still the golden standard that is accepted by many researchers. Therefore, we will be using the foot switch signal as a reference of the true heel strike and toe off events received from one foot.

Two foot switches were attached to an insole of the right foot shoe. The corresponding positions of the insole selected for attachment are respectively the subject's 1^{st} metatarsal bone (body) and calcaneal tuberosity. The foot switch signal was processed by using a threshold value set at 90% of the maximal value. Hence, all values more than or equal to 90% of the maximal value will be recognized as "on". Otherwise, the signal will be recognized as "off".

The accelerometer and the foot switches were connected to a portable data acquisition device (weight: 115g) that comprises a microprocessor MSP430F149 (Texas Instrument, Texas) and a wireless BlueTooth (BT) transceiver for wireless data transmission. The collected analog acceleration signals and foot switch signal were sampled at 512Hz with 10-bit resolution. All sampled and converted digital data were transmitted to the host computer for post-processing and result comparisons.

All subjects were asked to walk along a 10m straight walkway in a corridor for performing gait trials. The flat surface of the walkway is paved by cement. There were no obstacles or barriers placed on the track. All subjects were also asked to perform 9 gait trials in slow (1m/s), and median (1.2m/s) walking speeds.

B. Control scheme

All collected digital data was analyzed with MATLAB (Mathworks, Natick, MA, U.S.A.) in a host computer. A feed-forward back-propagation Neural Network (NN) model was built as a predictor for gait event prediction by using MATLAB. The control strategy of the pelvic motion driven electrical stimulator system is illustrated in Fig. 1.

Firstly, the predictor calculated the digitized acceleration data to generate the estimated gait events. Secondly, the resultant gait events were used as the information for commanding the electrical stimulator. Finally, the electrical stimulator was activated to help tibialis anterior muscle contract and perform ankle dorsi-flexion in order that the foot is kept away from dragging during walking.

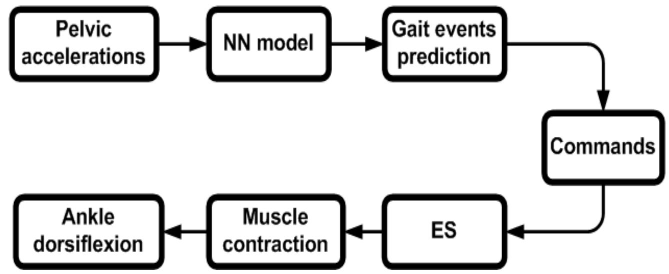

Fig. 1.The control strategy of the pelvic motion driven electrical stimulator system

III. System Design

The system is designed to stimulate the tibialis anterior muscle by referencing the real time predictions of the accelerometer worn on the ASIS. A portable pelvic motion driven electrical stimulator system (weight: 419g) is implemented accordingly. Details of the portable pelvic motion driven electrical stimulator system is illustrated in Fig. 2.

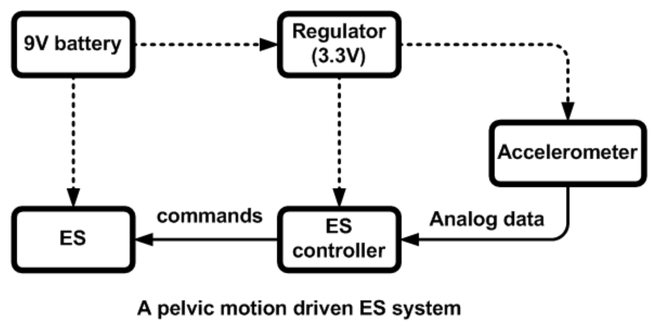

Fig. 2 The portable pelvic motion driven electrical stimulator system includes a tri-axis accelerometer, a commercial dual-channel ES, and an ES controller unit.

The system includes a compact low cost tri-axis accelerometer (LIS344ALH, STMicroelectronics Ltd., Geneva, Switzerland size: 4x4x1.5mm, range: ±2g, weight: 2g), a commercial portable dual channel neuromuscular electrical stimulator (Respond Select, Empi, Inc., St. Paul, MN, weight: 304g), and an ES controller circuit with a microprocessor MSP430F149 (weight: 113g). In order to avoid malfunctions that are caused by overloading the microprocessor, only the combination of ML and AP accelerations were used as the input information for the NN model. The final version of the NN model prediction will be applied as the control strategy of the ES controller unit in order to execute real-time gait predictions in a walking cycle. The placement of each element in the portable pelvic motion driven electrical stimulator system is shown in Fig. 3.

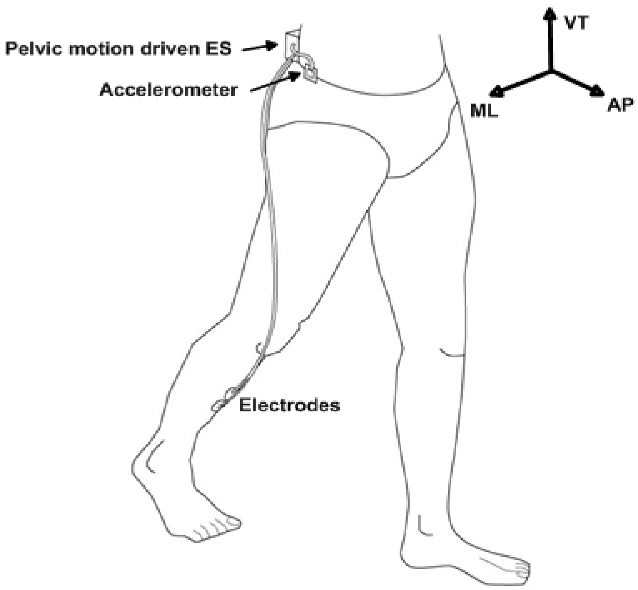

Fig. 3 The portable pelvic motion driven electrical stimulator system

IV. Preliminary Results & Discussions

All of the measured data including the pelvic acceleration data in AP and ML axes and gait events were analyzed and processed by MATLAB. From our example shown in Fig.4, we noticed that the acceleration in the ML axis is presented as a waveform that is nearly periodic. Therefore, it is readily verified that the signal collected from the ML axis will dominate the timing of the heel strike and toe off events. However, from our past trials, the acceleration data in the AP axis should also be utilized when gait event predictions require ultimate precision. This is because the approximate periodic waveform induced by pelvic acceleration in the ML axis might not provide enough information for predicting the heel strike and toe off events.

Fig. 4 also shows the sequence of a gait cycle predicted by a NN model. The predicted gait events matched quite well with the reference signals collected from foot switches (shown in Fig. 4 (c)) except for the error initializing steps that were caused by excessive forward trunk motion. The processed signal excluding the initializing step is shown in Fig. 4 (d), which gives us an even better result. The magnitude of electrical stimulation to subject's tibialis anterior muscle is shown in Fig. 4 (e).

Although an accelerometer worn on the pelvis could be used as an alternative device for foot switches, the excessive trunk motion of the initializing step, which is aperiodic, will influence accelerations in the prediction of heel strike. Nevertheless, the predicted gait events matched quite well with the signals from the reference foot switches, especially during periodic gait cycles after the initializing steps.

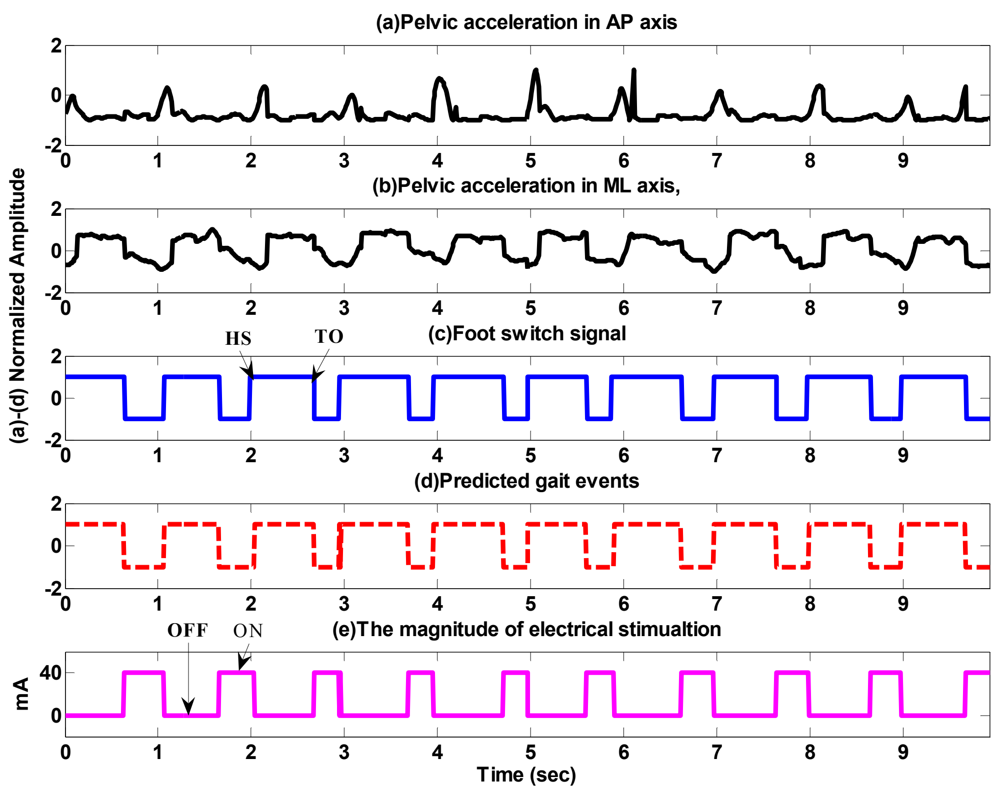

Fig. 4 Normalized signals at walking speed 1m/s (a) pelvic acceleration in AP axis, (b) pelvic acceleration in ML axis, (c) foot switch signal : heel strike(HS) and toe off (TO) (d) Predicted gait events by NN model(--), (e) The magnitude of electrical stimulation to anterior tibialis muscle

V. Conclusion

In past decades, the foot switches provided a common and useful solution for driving the FES assisted walking system for drop foot treatment. However, the reliability and durability of the foot switches has always been a problem yet to be solved. In several of our past trials, it is observed that the heel foot switch placed in the insole will detect false heel strike during swing phase (counteraction of the insole) and during normal walking (unclear contact). In contrast, the NN model for accelerometers used in our study predicts the timing only when true heel strike events occur. The pelvic motion driven electrical stimulator developed provides a simple and portable solution for gait restoration. It should also be noted that an accelerometer worn on the ASIS would avoid the problems found in foot switches, which includes mechanical degradation and deformation. Since it is comparatively easier for hemiplegic patients to perform pelvic motions, it is also anticipated that the implemented system will prevent muscle synergy. In the near future, we will be recruiting subjects of mild and severe hemiplegia for further research in order that an improved predictor for gait events can be applied clinically.

References

[1] M. W. Whittle, "Gait Analysis : an introduction", *Oxford: Butterworth-Heinemann*, 2001. 964, pp. 15–64.

[2] J. Perry, Gait Analysis: Slack Inc., 1992

[3] H. H. Liberson WT, Scott D, Dow M., "Functional electrotherapy : stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients," *Arch Phys Med Rehabil*, vol. 42, pp. 101-105, 1961.

[4] G. M. Lyons, T. Sinkjaer, J. H. Burridge, and D. J. Wilcox, "A review of portable FES-based neural orthoses for the correction of drop foot," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 10, pp. 260-279, 2002.

[5] A. Mansfield and G. M. Lyons, "The use of accelerometry to detect heel contact events for use as a sensor in FES assisted walking," *Medical Engineering & Physics*, vol. 25, pp. 879-885, 2003.

[6] D. Rongching, R. B. Stein, B. J. Andrews, K. B. James, and M. Wieler, "Application of tilt sensors in functional electrical stimulation," *Rehabilitation Engineering, IEEE Transactions on*, vol. 4, pp. 63-72, 1996.

[7] P. C. Sweeney and G. M. Lyons, "Fuzzy gait event detection in a Finite State Controlled FES Drop Foot Correction System," *J. Bone Joint Surg. [BR]*, vol. 81-B, p. 93, 1999.

[8] A. M. Sabatini, C. Martelloni, S. Scapellato, and F. Cavallo, "Assessment of walking features from foot inertial sensing," *Biomedical Engineering, IEEE Transactions on*, vol. 52, pp. 486-494, 2005.

[9] I. P. I. Pappas, M. R. Popovic, T. Keller, V. Dietz, and M. Morari, "A reliable gait phase detection system," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 9, pp. 113-125, 2001.

[10] K. Aminian, B. Najafi, C. B a, P. F. Leyvraz, and P. Robert, "Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes," *Journal of Biomechanics*, vol. 35, pp. 689-699, 2002.

[11] B. Auvinet, G. Berrut, C. Touzard, L. Moutel, N. Collet, D. Chaleil, and E. Barrey, "Reference data for normal subjects obtained with an accelerometric device," *Gait & Posture*, vol. 16, pp. 124-134, 2002.

[12] J. J. Kavanagh, S. Morrison, D. A. James, and R. Barrett, "Reliability of segmental accelerations measured using a new wireless gait analysis system," *Journal of Biomechanics*, vol. 39, pp. 2863-2872, 2006.

[13] Y. Shimada, S. Ando, T. Matsunaga, A. Misawa, T. Aizawa, T. Shirahata, and E. Itoi, "Clinical Application of Acceleration Sensor to Detect the Swing Phase of Stroke Gait in Functional Electrical Stimulation," *The Tohoku Journal of Experimental Medicine*, vol. 207, pp. 197-202, 2005.

[14] B. L. D. C. Vaughan, and J. C. O'Connor, "Dynamics of Human Gait: Human Kinetics", 1992.

[15] J. R. a. J. G. Gamble, "Human Walking", 2nd edition: Williams&Wilkins, 1993.