J. Biomed. Eng. Res.
Vol.26, No.3, 145-150, 2005

Development of a Portable Gait Phase Detection System for Patients with Gait Disorders

Seung Chan Ahn, Sung Jae Hwang, Sung Jae Kang, Young Ho Kim

Department of Biomedical Engineering and Institute of Medical Engineering, Yonsei University
(Received January 17, 2005. Accepted April 26, 2005)

Abstract: A new gait detection system using both FSR (force sensing resistor) sensors and a gyrosensor was developed to detect various gait patterns. FSR sensors were put in self-designed shoe insoles and a gyrosensor was attached to the heel of a shoe. An algorithm was also developed to determine eight different gait transitions during four gait phases: heel-strike, foot-flat, heel-off and swing. The developed system was evaluated from nine heathy mans and twelve hemiplegic patients. Healthy volunteers were asked to walk in various gait patterns: level walking, fore-foot walking and stair walking. Only the level walking was performed in hemiplegic patients. The gait detection system was compared with a optical motion analysis system and the outputs of the FSR sensors. In healthy subjects, the developed system detected successfully more than 99% for both level walking and fore-foot walking. For stair walking, the successful detection rate of the system was above 97%. In hemiplegic patients, the developed system detected approximately 98% of gait transitions. The developed gait phase detection system will be helpful not only to determine pathological gait phases but also to apply prosthetics, orthotics and functional electrical stimulation for patients with various gait disorders.

Key words : Gait phase detection, Functional electrical stimulation, FSR sensor, Gyrosensor, Microprocessor

INTRODUCTION

Recently, patients who have damages in the central nervous system are increasing due to the industrial or traffic accidents and diseases such as cerebral palsy. A damage in the central nervous system causes motor and sensory disorders. As time passes after the damage, the sensory function recovers in some degree, but the motor does not.

The functional electrical stimulation (FES) is applied for the recovery of motor functions in paralysed muscles. FES of lower limbs for gait recovery uses a manual switch to trigger sequences of the electrical stimulation. The manual switch requires the subject's continuous attention, thus only a limited number of gait phases can be successfully applied with a push-button type manual switch. The determination of precise stimulation sequences is required for gait improvement in the future FES.

Various gait detection systems have been proposed to control FES walking. Vodovik et al.[1] used three force-sensing resistors for gait detection and distinguished onset/offset of stance and swing phases during walking. However, they could not identify detailed gait phases such as heel strike, foot flat, heel off and swing. Ott et al.[2] reported that a foot switch, due to the poor detection reliability, was not an appropriate solution to trigger stimulation sequences in a FES system for walking. Ng and Chizeck[3] used goniometers to measure hip, knee, and ankle joint motions and classified five different gait phases using a fuzzy model. Nevertheless, this method showed frequent detection errors. Kostov et al.[4], using a goniometer, presented a method to evaluate FES walking for patients with foot drop. Dai et al.[5] used combinations of tilt sensors and inclinometers to trigger a FES system for compensating foot drops. Even though they provided information only on the transition between stance and swing phases, other detailed gait phases could not be distinguished. Tong and Grant[6] placed two gyrosensors on the thigh and on the shank, and could detect gait phases by measuring knee angles during walking. Willemsen et

This research was supported by the Program for the Training of Graduate Students in Regional Innovation which was conducted by the Ministry of Commerce, Industry and Energy of the Korean Government.
Corresponding Author: Young Ho Kim, (220-710) Dept. of Biomedical Engineering, Yonsei University, 234, MaeJi, Heungup, Wonju, Kangwon
Tel. 033-760-2492 Fax. 033-760-2197
E-mail. yhkim@dragon.yonsei.ac.kr

al.[7] placed accelerometers below the knee joint, to determine stance and swing phases during the gait cycle. Williamson and Andrews[8] mounted three accelerometers on the shank and applied a machine-learning algorithm to detect transitions among five gait phases during walking. However, this method also showed frequent detection errors because of the occasional signal chattering. Most previous gait detection systems have neither be used to trigger a FES system and nor be applied to distinguish detailed gait phases in pathological walking due to frequent detection errors.

In this study, a new gait phase detection system using both FSR sensors and a gyrosensor was developed to detect various gait patterns such as level walking, forefoot walking and stair walking. It was also applied to detect pathological gait transitions in hemiplegic patients. In addition, the accuracy and the reliability of the developed gait phase detection system were performed by synchronizations with a three-dimensional motion analysis.

MATERIALS AND SYSTEM DESIGN

Hardware Description

The gait phase detection system for this study used combinations of two different types of sensors: 1) four FSR sensors to measure forces exerted by the foot during walking and 2) a gyrosensor to measure angular velocity of the foot.

Fig 1 represents the placement of FSR sensors and a gyrosensor for the gait detection system.

The FSR sensor (MA-152, Motion Lab System Inc., U.S.A.) was a small flat resistor whose resistance changes nonlinearly with the applied force. Totally four FSR sensors were inserted in each self-designed polyurethane insole. FSR sensors were used as ON/OFF switches to indicate weight bearing, which was achieved by measuring the voltage drop across each FSR sensor connected in a voltage divider circuit. One of four FSR sensors placed underneath the heel, two underneath the 1st and the 4th heads of metatarsal bones and one underneath the hallux[9, 10]. A gyrosensor (ENC-03J, Murata, Japan) attached to the posterior aspect of the shoe for measuring angular velocity of the foot.

The control unit, attached in the waist, acquires sensor outputs at a sampling rate of 240Hz, changes them into digital values and classifies into different gait phases by a logical algorithm using a microprocessor (PIC16C73). Each classified gait phase was transmitted to a PC by a Bluetooth module (Promi-ESD, Initium, Korea). Data from the control unit was displayed in four different gait phases by a Labview program.

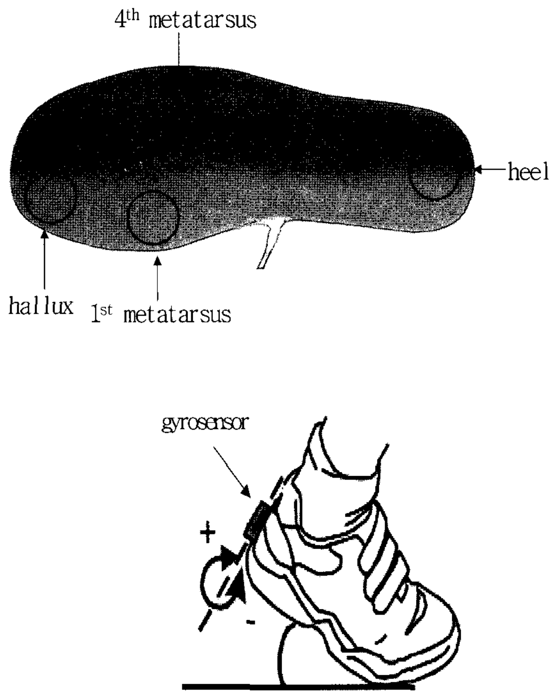

Fig. 1. Placement of the sensors used by the developed system

The Gait Phase Detection Algorithm

A normal gait cycle is divided into four different gait phases: HS (heel strike), FF (foot flat), HO (heel off), SW (swing). In this study, an algorithm for the gait phase conversion into totally eight transition events (T1~T8) can distinguish pathological gait events as well as normal ones using data acquired from FSR sensors and a gyrosensor. T1~T4 represent normal gait transitions and T5~T8 indicate pathological transitions or other than level walking events. Fig 2 describes the gait phase detection algorithm.

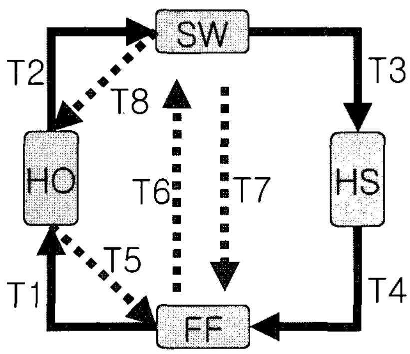

Fig. 2. Gait phase detection algorithm

Note: We assume that the subject is viewed from the both sides and clockwise rotations are considered positive. The symbol φ represents the inclination angle of the heel with respect to the ground and φ_{th} is the threshold for the detection of the heel off phase.

Normal gait

T1: (foot flat → heel off) In the foot flat phase, the algorithm waits for the beginning of the heel off phase. The heel off phase is detected when the heel FSR sensor is not pressed and the inclination angle of the heel with respect to the ground φ exceeds a given threshold angle φ_{th}(3°).

T2: (heel off → swing) In the heel off phase, the algorithm anticipates the transition to the swing phase. The condition for the transition to the swing phase is that none of the FSR sensor is pressed and that the rotation of the heel changes from positive to negative direction.

T3: (swing → heel strike) In the swing phase, the algorithm waits for the transition to the heel strike phase, which begins with the initial contact of the heel with the ground.

T4: (heel strike → foot flat) After the heel strike, the next phase is foot flat, which begins when both the front and rear parts of the foot touch the ground. This event is detected when the heel FSR sensor and at least one of the front FSR sensors are pressed.

Pathological gait or other than level walking events

T5: (heel off → foot flat) If the subjects lifts the heel and then places it back onto the ground (without going into a swing phase, as in the normal walking), this event is detected in the gait phase detection algorithm by a transition from heel off to foot flat. If the status of the heel FSR sensor is pressed during the heel off phase, the algorithm transits to foot flat phase.

T6: (foot flat → swing) In the first of a sequence of steps, the foot does not go through a true heel off phase but moves directly from foot flat to swing phase. Such a transition takes place under the condition that none of four FSR sensors is pressed and that the gyrosensor signal indicates a negative angular velocity of the foot.

T7: (swing → foot flat) The heel strike phase is too short to be detected as a distinct event. In this case the algorithm transits from the swing phase directly to the foot flat. The condition for this transition is that the heel FSR sensor and at least one of the front FSR sensors is pressed or that the angular velocity and its derivative are close to zero.

T8: (swing → heel off) After the swing, the next phase is heel off (without going into heel strike and foot flat, as for normal walking). This event is detected in the gait phase detection algorithm by a transition from heel off to stance. If the status of the front FSR sensors are pressed during the swing phase, the algorithm transits to heel off phase.

EVALUATION OF THE SYSTEM

Accuracy Evaluation Experiment

To evaluate the accuracy of the developed gait phase detection system, we have compared the output of the developed system with the measurements obtained by an optical motion analysis system and force plates. Totally nine healthy male volunteers (age: 26.7±1.6 years, weight: 76.1±4.4kg), attached reflective markers based on the Davis protocol[11], performed level walking. Marker's trajectories and vertical ground reaction forces were used to extract reference gait phase signals for evaluating the accuracy of output signals from the developed system.

Table 1 is the criteria to measure the accuracy of the developed gait phase detection system during level walking.

The delay time was defined by the time difference between detections by the optical motion analysis system and by the developed system. Table 2 is the delay time of the developed system for detecting gait phases in level walking. The output of the developed system correlated well with reference gait phase signals.

Table 1. Criteria to measure the accuracy of the developed gait phase detection system during level walking, synchronized with the three-dimensional motion analysis system

Gait Phases	Detection Methods
Swing ⇨ Heel Strike	When the vertical ground reaction force is generated
Heel Strike ⇨ Foot Flat	When the vertical position of heel marker increased its minimum, and the vertical position of toe marker stoped decreasing and maintained its minimum
Foot Flat⇨ Heel Off	When the vertical position of heel marker exceeded the threshold of 20mm
Heel Off ⇨ Swing	When the vertical ground reaction force is disappeared

However, time delays of the developed system signal relative to the reference signal were observed in the heel strike, foot flat and swing. Time delays in detecting four gait transitions relative to the reference signal were approximately 56±4.2ms for heel strike, 62±1.5ms for foot flat, 40±14.0ms for heel off, and 72±4.4ms for swing.

Reference signals were based on marker's trajectories and vertical ground reaction forces, but on the other hand, the gait detection in the developed system was dependent upon FSR sensor signals. To detect heel strike, the reference signal from swing to heel strike switched from OFF to ON when the vertical ground reaction force is just generated. On the other hand, the developed system used the time when only the FSR sensor at the heel switched from OFF to ON. To define swing, time delay can be explained in a similar fashion. To define foot flat and heel off in the reference signal, the trajectory of the heel marker was used, but contact informations based on FSR sensors were not precise, again due to the inherent characteristic of FSR sensors. However, the accuracy of detection in the developed system is good enough, since 60Hz of sampling rate was used to capture marker trajectories for the reference signal.

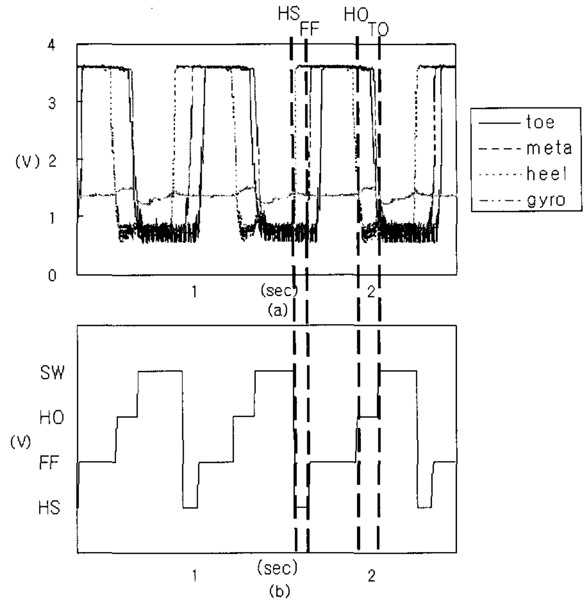

Fig. 3. Output signals of sensors and gait phase detection results in treadmill level walking

Reliability Evaluation Experiment

Nine healthy males and twelve chronic hemiplegic (more than six months after the revelation) patients (7 men and 5 women, age: 52±5.9 years, weight: 55.5±7.5kg) who has abilities to walk independently were chosen to evaluate the reliability of the developed system in different walking conditions. For healthy subjects, the final output of the developed system was compared with output signals from both FSR sensors and a gyrosensor in various walking conditions such as level walking, forefoot walking and stair walking. Level walking and forefoot walking was performed on a treadmill, and stair walking was made inside the building.

Fig 3(a) shows output signals of four FSR sensors (located at hallux, the two metatarsal bone and the heel) and a gyrosensor attached to the posterior aspect of a shoe, in treadmill level walking. Fig 3(b) shows final gait detection results from the developed system.

Fig 4 shows the final outputs from the developed system and corresponding sensor signals in treadmill forefoot walking. In forefoot walking, the final output from the developed system skipped heel strike and foot flat, switching directly from the heel off to the swing.

Fig 5 and Fig 6 show the final outputs from the developed system and corresponding sensor signals in stair ascending and stair descending respectively. It is noted that the first contact with the ground after the swing is made by the front part of the foot in stair walking not by the heel as in level walking.

Table 2 is success rates of gait phase detection in

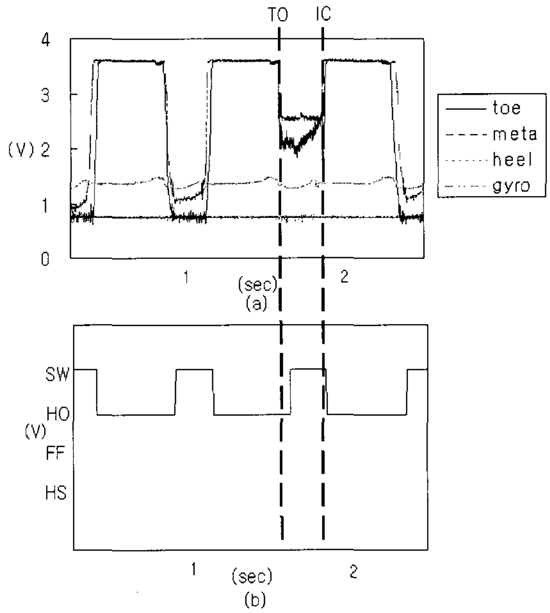

Fig. 4. Output signals of sensors and gait phase detection results in treadmill forefoot walking

level walking, forefoot walking and stair walking. Despite significant variations in the individual walking style, the developed system perfectly detected the gait transitions in level walking and 99% in forefoot treadmill walking. In stair ascending and in stair descending, the success rate of the gait phase detection in the developed system was above 97%.

Table 2. Success rate to detect gait phase in various walking pattern for healthy person

Steps	Level walking	Forefoot walking	Stair walking	
			Ascent	Descent
Total steps	407	325	234	204
Detected steps	407	322	228	199
Success rate (%)	100	99	97	97

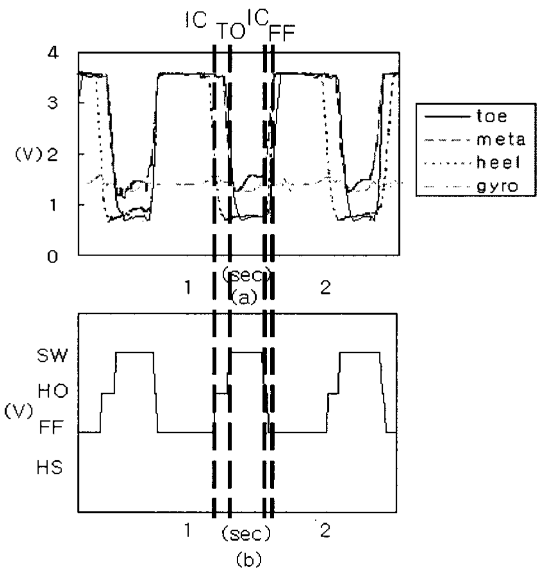

Fig. 5. Output signals of sensors and gait phase detection results in stair ascending

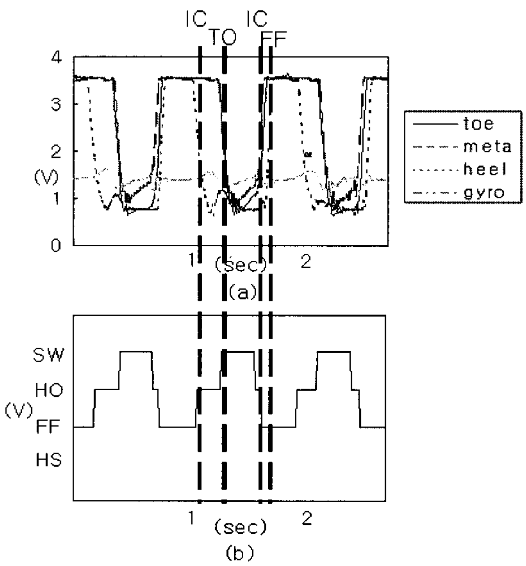

Fig. 6. Output signals of sensors and gait phase detection results in stair descending

Hemiplegic patients performed level walking at their self-selected walking speed. Hemiplegic gait can be characterized in three categories, based on which part of the foot contacted initially with the ground: forefoot contact, whole foot contact, and heel contact. In a typical hemiplegic gait, the initial contact of the affected limb is made rarely with the heel.

Fig 7 shows output signals of sensors and gait phase detection results for the case of forefoot contact. Final outputs of the gait detection system did not include heel strike phases, similarly in stair walking.

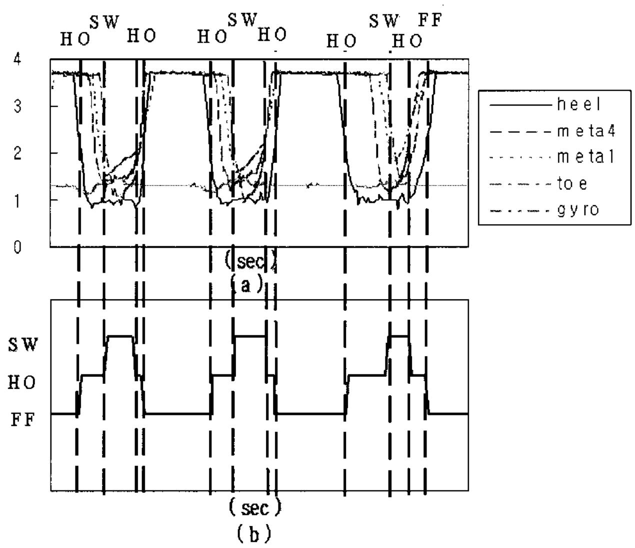

Fig. 7. Output signals of sensors and gait phase detection results in the front part of the foot walking at initial contact.

Fig 8 represents output signals of sensors and gait phase detection results for the case of whole foot contact. Fig 8 clearly showed that FSR sensors attached in metatarsal bones and the heel were pressed almost simultaneously, and thus the gait phase switched from swing to foot flat.

Table 3 summarizes the successful gait transition detection rates in level walking of hemiplegic patients. This success rate was similar to the one in forefoot walking for healthy males.

Table 3. Success rate to detect gait phase in level walking for hemiplegia patients

Position at initial contact	Total steps	Detected steps	Success rate(%)
Heel	322	315	98
Whole foot	159	154	97
Forefoot	365	359	98

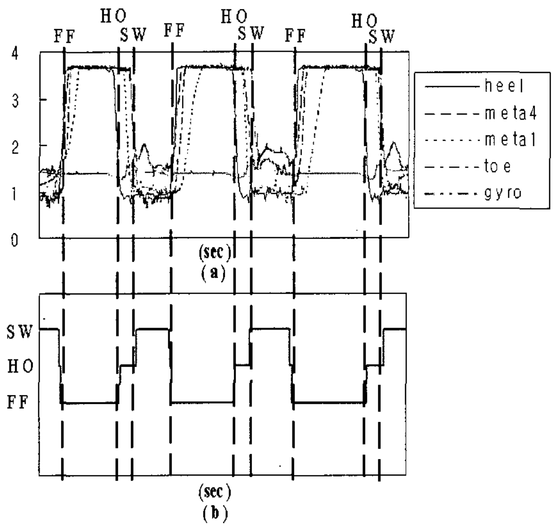

Fig. 8. Output signals of sensors and gait phase detection results in the whole foot walking at initial contact.

CONCLUSION

In this study, a new gait detection system using both FSR sensors and a gyrosensor was developed to detect gait pattern in various walking conditions such as level walking, forefoot walking and stair walking. The accuracy and the reliability of the developed system were evaluated in nine healthy males and twelve hemiplegic patients.

The gait phase detection delay did not exceed 72ms. In addition, the developed system achieved a success rate above 99% in level walking and forefoot walking. In stair walking, ascending and descending, the successful detection rate of the system was above 97%. Actual applications of the developed system to twelve hemiplegic patients verified that the developed system detected gait transition successfully about 98%.

The present gait phase detection system would be very helpful not only to determine pathological gait transitions but to apply prosthetics/orthotics and FES to patients with various gait disorders.

REFERENCES

[1] Vodovik, L., Kralj, A., Stanic, U., Acimovic, R. and Gros, N., "*Recent application of functional electrical stimulation to stroke patients in Ljubljana*", Clin, Orthop., Vol. 131, pp.64-70, 1978.

[2] Ott, E., Munih, M., Benko, H. and Kralj, A., "*Comparison of foot-switch and hand switch triggered FES correction of foot drop*", in Proc. 6th Vienna Int. Workshop FES, pp.22-24, 1998.

[3] Ng, S. K. and Chizeck, H. J., "*Fuzzy model identification or classification of gait events in paraplegics*", IEEE Trans. Fuzzy Syst., Vol. 5, pp.536-544, 1977.

[4] Kostov, A., Andrews, B. J., Popovic, D. B., Stein, R. B. and Armstrong, W., "*Machine learning in control of functional electrical stimulation systems for locomotion*", IEEE Trans. Biomed. Eng., Vol. 42, pp.541-551, 1995.

[5] Dai, R., Stein, R. B., Andrews, B. J., James, K. B. and Wieler, M., "*Application of tilt sensors in functional electrical stimulation*", IEEE Trans. Rehab. Eng, Vol. 4, pp.63-72, 1999.

[6] Tong, K. and Grant, H. M., "*A practical gait analysis system using gyroscope*", Med, Eng. Phys., Vol. 21, pp.87-94, 1999.

[7] Willemsen, A., Bloemhof, F. and Boom, H., "*Automatic stance-swing phase detection from accelerometer data for peroneal nerve stimulation*", IEEE Trans. Biomed. Eng., Vol. 37, pp.1201-1208, 1990.

[8] Williamson, R. and Andrews, B. J., "*Gait event detection for FES using accelerometers and supervised machine learning*", IEEE Trans. Rehab. Eng. Vol. 8, pp.312-319, 2000.

[9] Kang, S. J. and Kim, Y. H., "*Gait improvement of polio patients using an electromechanical KAFO*", Journal of the Korean Society of Precision Engineering, Vol. 20, No. 1, pp.39-46, 2003.

[10] Lee, K. W., Kang, S. J., Kim, Y. H. and Cho, K. H., "*Development of the automatic knee joint control system for a knee-ankle-foot orthosis using an electromechanical clutch*", J. Biomed. Eng. Res., Vol. 22. No. 4, pp.359-368, 2001.

[11] Davis, R. B., Ounpuu, S., Tyburski, D. and Gage, J. R., "*A gait analysis data collection and reduction technique*", Human Movement Sci, Vol. 10, pp.575-587, 1991.