Communications

A body-worn gait analysis system for evaluating hemiplegic gait

M.H. Granat*, D.J. Maxwell*, C.J. Bosch+, A.C.B. Ferguson*, K.R. Lees† and J.C. Barbenel*

*Bioengineering Unit, Wolfson Centre, University of Strathclyde, 106 Rottenrow, Glasgow G4 ONW, UK; †Biomedical Engineering Division, University of Twente, PO Box 217, 7500 AE, Enschede, Netherlands; ‡Department of Medicine and Therapeutics, Garden Institute, Western Infirmary, Glasgow G11 6NT, UK

Received February 1994, accepted June 1994

ABSTRACT

This paper describes a system for measuring the temporal parameters of hemiplegic gait. This system uses shoe insoles with sensors, acting as switches, placed under the heel, head of the first metatarsal, head of the fifth metatarsal and the big toe. This system is able to monitor gait for up to 10 min and can be used by the patient over any surface. Parameters for evaluating hemiplegic gait are defined, including scuffing during swing and the degree of inversion during stance.

Keywords: Gait, hemiplegia, temporal parameters, insoles

INTRODUCTION

The measurement of temporal and spatial parameters has been used to assess normal and pathological gait. This has given an insight into the mechanisms of walking and has been used to evaluate treatment regimes. Opto-electronic systems such as the VICON [Oxford Metrics, Oxford, UK] and ELITE [BTS, Milan, Italy] can provide detailed kinetic and kinematic information. These systems are, in general, powerful and flexible but can only capture data from one sample stride of any walk. They are also expensive, require a high degree of specialized expertise to operate and need a dedicated laboratory.

Different walkway systems have been developed in an attempt to provide a gait analysis system more applicable to the clinic. These systems fall into three basic categories; conductive mats, resistive walkways and walkways consisting of a matrix of switches. Conductive mats have been used to measure the temporal parameters of gait1. The subject wears shoes with conductive soles and walks over a conductive walkway. Contact between the subject's shoes and the walkway surface completes an electrical circuit: Timing of the open and closed circuit conditions gives stance and swing times. Resistive walkways have also been used to measure the temporal and spatial parameters of gait in which conductive material placed under the shoe of the subject alters a measured resistance2,3. Walkways consisting of arrays of sensors have been used to measure stride length, step length, base width, foot angle and temporal parameters4 their resolution being determined by the density of sensors.

All these systems have several disadvantages these being:

(a) lack of portability
(b) require a dedicated laboratory
(c) gait is evaluated on the surface defined by the system
(d) derived parameters do not always give relevant information on the specific problems of hemiplegic gait.

Some portable systems have been developed5-8, but although they address some of the problems
of the "fixed" systems they do not provide enough appropriate information for a clinical assessment of the gait.

To monitor a patient's response to a treatment programme analysis of the patient's gait is best carried out in a physiotherapy department. Constraints of time and space require a simple objective measure of the relevant parameters of the gait.

In order to devise a clinical system for evaluating hemiplegic gait the specific gait abnormalities of the patient population need to be considered and defined in relevant terms for use in a portable system. Hemiplegic gait is characterized by a highly asymmetric gait pattern and this is manifested by reduced flexor activity on the affected side. There is generally an imbalance of subtalar muscles with weakness of the evertors and/or spasticity of the plantar flexors and an imbalance of ankle musculature with weakness of dorsiflexors and/or spasticity of the plantar flexors. This generally results in inversion and plantar flexion of the foot. As a result of drop foot during the swing phase the foot often scuffs the ground. This problem of scuffing has neither been addressed nor quantified by existing gait analysis systems and can cause errors with some systems due to scuffing being interpreted as stance. This gait deficit is more accentuated when the person is walking on uneven ground or over carpet.

It was our aim to construct a portable, body-worn gait analysis system that would be minimally encumbering, could be used in a clinical setting and which would quantify the parameters significant to hemiplegic gait.

**DESIGN**

Shoe insoles were used to measure the foot-floor contact patterns which were recorded on a commercial data-logger. At either end of the walkway there was an infra-red (IR) beam which was used to time the walk. The instant the subject broke the IR beam was also recorded on the data-logger using IR sensors mounted on the shoulder of the subject. The distance between the IR beams defined the length of the walkpath. A sketch of the overall system is given in Figure 1.

**Shoe insoles**

To detect the timing of the foot-floor contact patterns shoe insoles were fabricated. These insoles had four force sensitive resistors (FSRs) [Interlink Electronics, Luxembourg], acting as switches, placed at the position of the heel, head of the first metatarsal, head of the fifth metatarsal and the big toe. They were mounted on thin plastic film to the shape of the subject's feet. The FSRs are thick film devices which exhibit a decreasing resistance with increasing force applied to the device surface. The FSR at the heel was $1\frac{1}{2}$ square and the other FSRs were circular with a radius of $\frac{3}{4}$. Each FSR formed an arm of a potential divider and the analogue signal from each FSR was taken to the data encoder.

**Data encoder**

The data-logger had a fixed memory capacity of 64 Kb. In order to maximise the data sampling period, a simple data reduction and compression technique was employed. Each FSR analogue signal was converted to a digital ON/OFF signal. The ON/OFF threshold was adjustable and was set for transition to occur at an average loading of approximately 1 N to ensure that there was a digital OFF signal with unloaded tightly laced shoes. The four digital signals from the FSRs of each foot and the digital signal from the IR detector were then "added" by an eight bit digital to analogue converter. The output of each FSR was represented by one bit of the eight bit number with the heel FSR giving the most significant bit. The data encoder was powered by a single 9V PP3 battery.

All data were collected on the data-logger [Penny and Giles, Gwent, UK]. Using the above technique it was possible to store the four digital FSR signals from one insole and the digital IR signal on one channel of the data logger. A sampling frequency of 50 Hz was used and this permitted a total recording time of approximately ten minutes. This was more than adequate to collect representative data from a single subject. At the end of the test the data was downloaded from the data-logger to a Personal Computer.

**Optical timing system**

IR emitters and sensors were mounted on an upright pole opposite a pole carrying a reflector. These beams demarcated the ends of the walkway. The circuit was designed so that when the IR beam was broken the IR emitter was turned off. A logic circuit was used to start a timer which was stopped when the second IR beam was broken. The logic circuit allowed timing to occur in both directions, a significant advance over unidirectional systems which require the subject to return to a start position for each walk.

Attached to each shoulder of the subject was a small IR sensor. These detected the IR signal as the subject approached the IR beam. When the subject broke the IR beam the IR emitters were switched off. This transition, from ON to OFF, was detected by the shoulder sensors and the digital output from these sensors was "added" to the input on one of the channels of the data-logger. The transition from ON to OFF for the IR signal acted as a marker on the data for the start and end of the walk.

**Data processing**

The data was stored on floppy disk, each disk holding three hours of data. A program, written in Turbo Pascal [Borland International], decoded the data giving the ON/OFF patterns with time for all the signals. This program graphically displayed these patterns giving a visual representation of the walk. Two foot-floor contact patterns are shown in Figures 2 and 3 from hemiplegic sub.
A body-worn gait analysis: M.H. Granat et al.

IR receivers

interface box & datalogger

reflector

IR emitter & receiver

timer unit

battery

Figure 1. The gait analysis system. The data encoder and data logger are worn on a belt around the waist. The shoulder infra-red receivers marked the start and end of the data on the data logger and the system was used with the subject starting at either end of the walkpath.

Figure 2. Foot-floor contact patterns from a subject with a left hemiparesis. These eight traces represent the status of the signals from the eight FSRs. When the switch is ON the trace goes up and when OFF the trace goes down. The traces are coded as to the leg and position of the FSR (L = left, R = right, BT = big toe, 1M = first metatarsal, 5M = 5th Metatarsal and H = heel). The right leg shows a clear heel strike and toe off phase. On the left the foot contacts the ground evenly and there are two instances of scuffing from the LBT at about 5 seconds and 6.5 seconds.

Figure 3. Foot-floor contact patterns from a subject with a right hemiparesis. These eight traces represent the status of the signals from the eight FSRs. When the switch is ON the trace goes up and when OFF the trace goes down. The traces are coded as to the leg and position of the FSR (L = left, R = right, BT = big toe, 1M = first metatarsal, 5M = 5th Metatarsal and H = heel). This gait is slower than in Figure 2 with both feet showing abnormal foot-floor contact patterns. On the right foot there is virtually no contact of the first metatarsal indicating that this subject is walking on the lateral border of his foot with pronounced inversion.

Objects with different gait abnormalities. The data of interest was then exported to a file in ASCII format.

An analysis program [Turbo Pascal] operated on these ON/OFF values to calculate the outcome measures. To interpret the abnormal pattern of the gait robust rules were devised. These rules were based on the observation that the unaffected leg shows a clear swing-stance pattern. From this pattern the swing-stance periods of the affected leg were inferred and then the outcome measures could be calculated.

Definition of outcome measures

Drop foot in the swing phase results in poor placement of the foot during the following stance phase. Clinical observations have shown that this results in absent or poor heel strike, ankle instability due to foot inversion on floor contact and a highly asymmetric swing and stance period. The outcome measures were defined to quantify these aspects of the foot-floor contact. The outcome measures were defined as follows:

**Heel strike**

This quantified heel contact at the start of the stance phase. This was calculated as the average time for which the heel switch was ON at beginning of each stance period. This was expressed as a percentage of total foot contact time.

**Inversion**

This measured the degree of inversion of the foot during the stance phase. This was quantified by calculating the difference of ON times between the 5th metatarsal and the 1st metatarsal switches. This was expressed as a percentage of continuous metatarsal-floor contact time. A value of +100% indicated that there was no contact under the 1st metatarsal, a value of 0% indicated equal contact times and a

392
value of \(-100\%\) indicated that there was no contact under the 5th metatarsal.

**Scuff**

This quantified the ‘scuffing’ (foot contact during swing phase). A ‘scuff’ was indicated by any foot switch(es) registering contact during the swing phase of that leg. The total number of ‘scuffs’ in each run was the measure of *scuff*.

**Symmetry**

This quantified the swing symmetry of the gait pattern. This was calculated as the ratio of swing time of unaffected leg to swing time of affected leg. Swing time was calculated as the time between last floor contact of the foot to the first floor contact of the same foot.

**Stride length**

Stride length was defined as the distance from heel strike of the unaffected leg to heel strike of the same leg. It was calculated by multiplying the average speed by the average time per stride for a given walk.

**Speed**

Speed was defined as the walkpath length divided by the time taken to cross the IR beams.

**SYSTEM EVALUATION AND DISCUSSION**

To illustrate the effectiveness of the system the gait pattern of one subject was repeatedly examined over a number of weeks. The subject was a 62 year old male with a right sided hemiparesis and was recruited for this trial three months post CVA. During the first week (week 1) the subject was required to walk along a straight path 6 m in length. Five recorded walks were made on each day and this was repeated on five consecutive days. These tests were then repeated during weeks 5 and 11.

The results demonstrate the asymmetry of the subject’s gait and quantify specific features. For the outcome measures of heel strike, inversion and scuff the results are presented for both the affected and unaffected legs (Figure 4). All differences between legs are highly significant \((p < 0.001, \text{ANOVA})\) except for scuff at week 11.

There was a highly significant \((p < 0.001, \text{ANOVA})\) improvement in speed and symmetry (Figure 4) from week 1 to 6 and weeks 6 to 11 but no change in stride length. There was a significant improvement in scuff (Figure 5) and together with the improved speed and symmetry indicates a general improvement in walking ability. The decline in the amount of scuffing is a very real benefit for the patient and the system clearly identifies this.

An improvement in symmetry was also demonstrated but over time there was no change in heel strike or inversion with both being highly abnormal. These outcome measures can therefore objectively measure a patient’s progress in a rehabilitation programme. There was no change in heel strike and inversion and it may be that the subject’s rehabilitation programme should target these areas.

![Figure 4](https://example.com/figure4.png)  
**Figure 4** Parameters of speed, stride length and symmetry with time for a subject with a right sided hemiparesis. At week one the subject was three months post CVA. The bars represent the means of the 25 walks with the 95% confidence intervals shown.

![Figure 5](https://example.com/figure5.png)  
**Figure 5** Parameters of heel strike, inversion and scuff with time for a subject with a right sided hemiparesis. At week one the subject was three months post CVA. The bars represent the means of the 25 walks with the 95% confidence intervals shown.

Virtually all gait analysis is performed with the subject walking along a linoleum type surface which is not representative of typical floor surfaces encountered by the patient. This system can evaluate gait over any surface and we have explored both carpeted surfaces and simulated uneven ground. There exist a few systems that allow gait to be evaluated over different surfaces but they offer only a limited amount of relevant information.

Rules for determining outcome measures can be adapted to examine features of interest for different gait pathologies and new rules for the analysis of the data can be easily incorporated into the existing software. As an example in a cerebral palsied child with spastic tendoachilles it could be expected that the big toe switch would be on during most of the stance phase. Any change in the foot-floor contact pattern could therefore be quantified by a change in the proportion of time.
the big toe was giving an ON signal at the end of the stance period.

The software and the logic for calculating the outcome measures could also operate on data collected by other foot insole systems or appropriate walkways based on other devices. The outcome measures can therefore be hardware independent but the actual values would depend on the precise alignment and characteristics of the sensing system.

This system has been developed specifically to evaluate hemiplegic gait. However as it operates only on foot-floor contact timings its limitations should be recognised. It was designed to be used as a stand-alone system but could be combined with additional sensor sets such as goniometers to yield additional information.

CONCLUSIONS

- This insole system together with the novel analysis techniques provides a simple method of objectively measuring some relevant characteristics of hemiplegic gait.
- The derived outcome measures represent clear clinical aspects of the gait and can monitor a patient’s progress in a rehabilitation programme.
- The software can be easily adapted to measure other parameters which are relevant to a particular gait pathology.
- This system, because of its ease of use, portability, minimal space requirement and ability to be used over any surface, is a useful clinical tool for gait evaluation in locomotor disorders.

ACKNOWLEDGEMENTS

The financial support of the Scottish Home and Health Department (K/CRED/4/C164) is gratefully acknowledged.

REFERENCES