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A practical gait analysis system using gyroscopes

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Abstract

This study investigated the possibility of using uni-axial gyroscopes to develop a simple portable gait analysis system. Gyroscopes were attached on the skin surface of the shank and thigh segments and the angular velocity for each segment was recorded in each segment. Segment inclinations and knee angle were derived from segment angular velocities. The angular signals from a motion analysis system were used to evaluate the angular velocities and the derived signals from the gyroscopes. There was a good correlation between these signals. When performing a turn the signals of segment inclination and knee angle drifted. Two methods were used to solve this: automatically resetting the system to re-initialise the angle in each gait cycle, and high-pass filtering. They both successfully corrected this drift. A single gyroscope on the shank segment could provide information on segment inclination range, cadence, number of steps, and an estimation of stride length and walking speed. © 1999 IPEM. Published by Elsevier Science Ltd. All rights reserved.

Keywords: Ambulatory monitor; Gait analysis; Gyroscope; Sensors

1. Introduction

Gait analysis has become a widely used clinical tool, and an increasing number of physical therapists and doctors are choosing suitable treatments for their patients based on the information from kinematic and kinetic data [1]. Kinematic data are also increasingly being used for the control of neural prostheses or functional electrical stimulation (FES) [2,3].

A complete gait analysis system uses an optical motion analysis system for kinematic data combined with force platforms for kinetic data. These systems are expensive, require a large space and cannot be used outside a laboratory environment. The capture volume is also limited to a few gait cycles. Therefore there has been much activity in trying to find alternative solutions for capturing gait information over a larger distance and outside a laboratory environment [3–10].

During the last decade, many sensors have been developed for industrial, robotics, aerospace and biomedical measurements using the continuously advancing circuit technology. These sensors are becoming more compact in size and lower in cost [4,5]. For gait analysis, electrogoniometers, accelerometers, inclinometers and force sensitive resistors (FSR) can be used to measure joint angles, linear acceleration, tilt angle relative to gravity and times of foot contact, respectively. A portable kinematic gait analysis system can be built using these small sensors. If a number of these sensors are used simultaneously, the system can become cumbersome and difficult to don/doff. A practical system must be small and easy to apply, and provide enough relevant information.

If the position and the orientation of each body segment is known, then it is possible to calculate all the kinematic data. In the aerospace industry, gyroscopes and accelerometers are widely used to provide information on position and orientation. It is theoretically possible to use the same techniques for gait analysis. The signals from accelerometers and gyroscopes are acceleration and angular velocity, respectively. The raw signals from accelerometers and gyroscopes have been used to quantify human daily activities [6–10]. Joint angles are commonly used in gait analysis and can be derived by the integration of angular acceleration or angular velocity. However, data obtained from integration can be distorted by offsets or any drifts.

To find the angular acceleration using accelerometers, a pair of accelerometers fixed on a rigid object is

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required. In order to eliminate any drift during integration, Morris (1973) [11] identified the beginning and the end of the walking cycles, and made the signal at the beginning and the end of the cycle equal. Willemsen et al. (1990) [12] developed a technique to find the joint angle without the need for integration, which used four accelerometers on each segment. The system used two metal bars with eight accelerometers for measuring a single joint angle. They also used a simplified version of their technique for the control of an FES system. Four accelerometers on a metal bar were used to calculate the joint acceleration, and different phases of gait could be detected for FES control without the need for the angular information [2].

Inclinometers have also been evaluated for use in controlling FES systems [3]. Inclinometers detect inertial forces. During the stance phase, when the angular acceleration is nearly zero, the inertial force is principally due to gravity, and the segment inclination can then be calculated. During the swing phase the angular acceleration affects the measurement and therefore inclination cannot be accurately calculated.

Another promising alternative is to use gyroscopes directly to measure the angular velocity without the signal being affected by gravity or any linear acceleration. Gyroscopes can therefore theoretically be used to calculate the segment inclination and the relative joint angle. During walking the movement of the lower body segments occurs mainly in the sagittal plane, so only single uni-axial gyroscopes would be required on each segment.

Heyn et al. (1996) [13] had showed that shank inclination could be measured with eight accelerometers and two gyroscopes fixed on two rigid metal plates. This experimental protocol did not include any turning which could be expected to effect the inclination. They also found that using these metal plates was cumbersome.

The aim of this study was to investigate the possibility of using uni-axial gyroscopes to design a practical gait analysis system. The gyroscopes would be fixed directly to the skin making the system easy to apply and reducing subject encumbrance. The first objective was to evaluate the angular signals and derived signals from gyroscopes and compare these with data from the motion analysis system (Vicon). The second objective was to evaluate the problem of drifting during turning and to investigate solutions to this problem.

2. Methods

The dynamic performance of the uni-axial gyroscopes was evaluated from data collected while a subject walked in a straight line in a gait laboratory. The principle of operation of the gyroscope is the measurement of the Coriolis acceleration of a vibrating device. It consists of a triangular prism made of a special substance called 'Elinvar'. If the prism is rotated about its sense axis the signal is proportional to the angular velocity. The gyroscope used was ENC-05EA (Murata, Japan), and the dimensions of this sensor were $20 \times 7.2 \times 10$ mm.

The gyroscope was fixed on both the shank and the thigh segments using a strap (Fig. 1). The sensing axis was along the medial–lateral direction so that the angle in the sagittal plane could be measured. Two subjects were used, an incomplete spinal cord injured (SCI) subject and an unimpaired subject. A motion analysis system (Vicon) was used to evaluate segment inclinations, segment angular velocities and knee angle using retroreflective markers attached to anatomical positions on the thigh and shank segments. Four FSRs were placed underneath the foot (one under each of the big toe, first metatarsal, fifth metatarsal and heel) and signals from these FSRs were used to detect different gait phases. All the signals were synchronously recorded using the Vicon system at a 50 Hz sampling frequency.

In the first 5 s of each experimental trial, the subject stood still in upright position to initialise the inclination angle and gyroscope offset. Then the subject walked at his preferred speed along the walkpath. Three sets of experiments were conducted to analyse the performance of the gyroscopes. The stride length, the gait cycle time and the speed of each walking session were calculated from the Vicon data.

In the first experiment, the signals from gyroscopes attached on two different positions of the shank on the unimpaired subject were compared. In the second experiment the signals from gyroscopes were compared

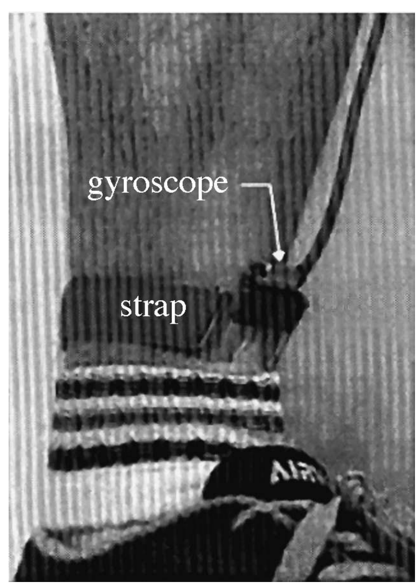


Fig. 1. Strap system with gyroscope. The gyroscope was attached to the strap. During walking, the strap was tied around the limb to secure the position of the gyroscope.

with the signals from the motion analysis system. In this experiment two gyroscopes were attached on the shank and thigh segments of the affected leg of the incomplete SCI subject. In the third experiment gyroscopes were attached on the shank and thigh segments of the unimpaired subject and the effect of turning was evaluated.

2.1. Experiment 1: Comparison between the signals from gyroscopes attached to two different positions of the shank

If two points, A and B, are in the same plane of a rigid body then the inclination, angular velocity and angular acceleration of both points will be identical. Signals from two different locations on the same plane on the same segment were evaluated. Two gyroscopes were attached on two different locations on the anterior aspect of the left shank (at the tibial tuberosity and 10 cm on the tibia proximal to the ankle joint) of the unimpaired subject. Data from four walking trials, each of 4.5 m, were recorded.

2.2. Experiment 2: Comparison of the signals from gyroscopes and the signals from the motion analysis system

Gyroscopes were attached on the anterior aspect of the thigh (10 cm above the patella) and the anterior aspect of the shank (10 cm on the tibia proximal to the ankle joint) of the incomplete SCI subject. Both gyroscopes were attached to the affected leg. The signals recorded from the gyroscopes were angular velocities. Segment inclinations and knee joint angle were derived from these angular velocities. Data from four walking trials, each of 4.5 m, were recorded.

2.2.1. Angular velocity

The gyroscope signals were compared with the angular velocities calculated from the marker set on the shank and thigh segments using the motion analysis system.

2.2.2. Inclination

The inclination on the shank and thigh were calculated by integration of the gyroscope signals (G) from the shank and thigh segments (Eq. (1)). In the first 5 s of each experimental trial, the subject stood still in an upright position to initialise the inclination angle and the gyroscope offset. The initial offset of the gyroscope was set using the average gyroscope values (G_{ave}) during this 5 s initial period. The inclination of shank and thigh was set to zero in this initial period.

$$\text{Inclination}_j = \frac{\sum_{i=0}^{j} G_i - G_{ave}}{\text{Sampling frequency}} \tag{1}$$

where G_{ave} is the integration constant, j represents the current sample and i represents the indexing.

2.2.3. Knee joint angle

The knee angle was calculated by subtracting the inclination of the thigh from the inclination of the shank.

2.3. Experiment 3: Evaluation of turning

Gyroscopes were placed on the anterior aspect of the thigh (10 cm above the patella) and the anterior aspect of the shank (10 cm on the tibia proximal to the ankle joint) of the unimpaired subject. The subject walked in a straight line for 4.5 m, then turned 180° and walked back to the starting point. Four trials were recorded.

2.3.1. Evaluation of the derived signals from the gyroscopes

All signals were compared as in the second experiment. Two approaches were used to solve the problem of drifting due to turning.

1. An automatic reset system was used to eliminate the drift due to turning. As walking is cyclical the inclination was reset within each gait cycle using a single gait event. Four FSRs underneath the foot were used to detect the mid-stance. By assuming that the shank and thigh segments were in the vertical position during the mid-stance the inclination values were automatically set to zero in each gait cycle. The peak of the summation signal from FSRs under heel and first metatarsal was used to define the mid-stance phase. The shank inclination from the automatic reset system was compared with the signals from the motion analysis system.
2. A high-pass filter with 0.3 Hz cut-off frequency was used to filter the inclination signals on the shank and thigh segments, and the derived knee angle was compared with the signals from the motion analysis system. This method shifts the signal to zero eliminating both drift and offset.

2.3.2. Gait analysis

The gyroscope signals were compared to gait events which were detected using FSRs. One gait cycle was defined from heel strike to the next heel strike and the gait cycle was normalised to 100%. Four gait events were defined in one normalised gait cycle: heel strike (HS), foot flat (FF), heel off (HO) and toe off (TO). Swing phase was the period between toe off and the end of the gait cycle.

The derived signals analysed in a normalised gait cycle in this experiment were angular velocity from the gyroscopes on the shank and thigh segments, and knee joint angle derived from the gyroscopes on the shank and thigh segments.

2.4. Performance analysis of the gyroscopes

Two criteria were used to evaluate the similarity between signals. These were:

1. The signals should be identical in the time domain and therefore the correlation coefficient should be close to one, and
2. The signals should be identical in value and therefore the root mean squared error (RMSE) or the normalised RMSE (NRMSE) should be close to zero.

2.4.1. Correlation coefficient (CORRCOEF)

The correlation coefficient was calculated to compare the signals after filtering. If the correlation coefficient had the value closed to + 1, then there was a linear relationship between these two signals in the time domain. The value of the correlation coefficient ranges from − 1 to + 1, and is used to represent the relationship between two signals in the time domain, (*i*,*j*).

2.4.2. Root mean square error (RMSE) and normalised root mean square error (NRMSE)

The root mean square error (RMSE) was used to analyse the average difference between the signals. If the value of the RMSE was small, then the signals were close to each other in time domain.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{\text{Number of samples}} (Sensor1\text{—}Signal_i - Sensor2\text{—}Signal_i)^2}{\text{Number of samples}}} \quad (2)$$

The normalised RMSE (NRMSE) used the standard deviation of the signal to scale the RMSE with respect to the standard deviation ($std(Sensor1\text{—}Signal)$). This was used to compare the accuracy between different signals which have different units and ranges. If the value of NRMSE was small, then these signals were closer to each other.

$$\text{NRMSE} = \frac{\text{RMSE}}{Std(Sensor1\text{—}Signal)} \quad (3)$$

3. Results

3.1. Comparison between the signals from gyroscopes attached on two different positions of the shank

In the first experiment, the subject walked with a stride length of 1.15 m, a gait cycle time of 1.5 s and a speed of 0.77 m/s. The angular velocity signals are shown in Fig. 2.

We have shown that most of the frequency spectrum of the angular signals during walking was under 4 Hz [14]. Both physical sensor signals were therefore filtered with a 4th order low-pass Butterworth filter with 4 Hz cut-off frequency. The peak of the cross-correlation lay on the zero line and this demonstrated that these two signals were almost identical with no phase shift between them.

The CORRCOEF was 0.94, the RMSE was 14.41 and the NRMSE was 0.40 between the signals from these two gyroscopes. The comparison showed that the signals from these two gyroscope were almost identical.

3.2. Comparison of the signals from gyroscopes and the signals from motion analysis system

In the second experiment, the subject walked with a stride length of 0.70 m, a gait cycle time of 2.32 s and a speed of 0.30 m/s. All the signals from gyroscopes and the motion analysis system were filtered with the same low-pass Butterworth filter. The signals derived from the gyroscopes were compared with the signals derived from the motion analysis system (Figs. 3 and 4 and Table 1).

3.3. Evaluation of turning

The subject walked with a stride length of 1.17 m, the gait cycle time was 1.6 s and the speed was 0.73 m/s. The angular velocity from the gyroscope maintained a high correlation with the motion analysis system throughout the whole walk but the derived signals from the gyroscope drifted during and after the turn (Fig. 5).

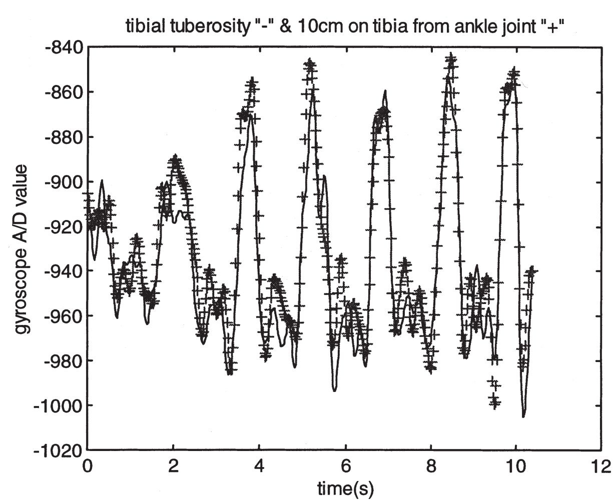


Fig. 2. Signals from two gyroscopes on different positions on the shank. The signal of the gyroscope on the tibial tuberosity ‘ − ’ and the signal of the gyroscope on the tibia 10 cm from the ankle joint ‘ + ’ after the low-pass filter are shown.

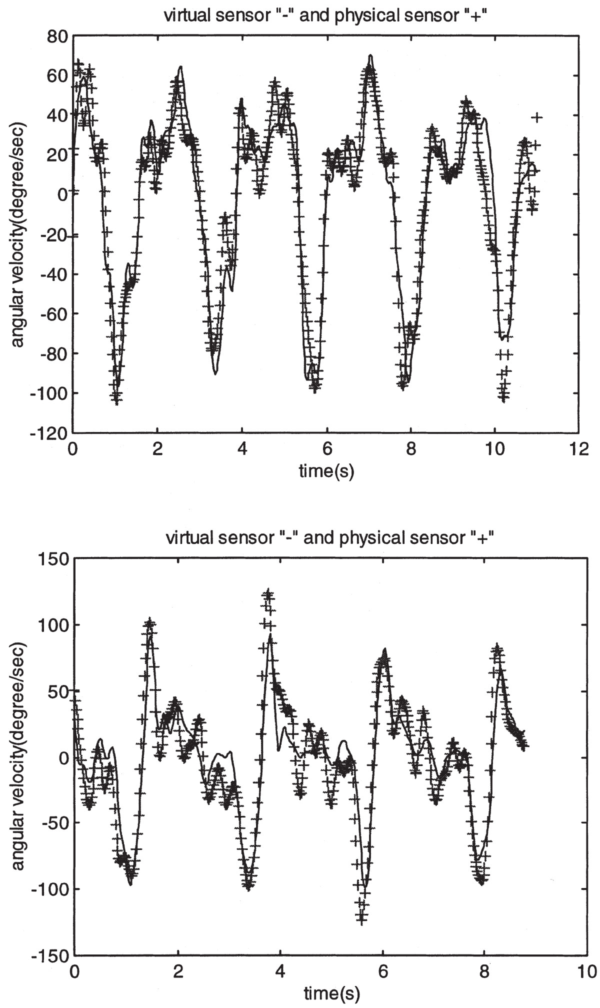


Fig. 3. Evaluation of gyroscope data on the shank and thigh on the incomplete SCI subject. The signal from Vicon data ‘ − ’ and the signal from gyroscope ‘ + ’ after the low-pass filter are shown. (a) The gyroscope signals from the shank and the signal calculated from the motion analysis system. (b) The gyroscope signals from the thigh and the signal calculated from the motion analysis system.

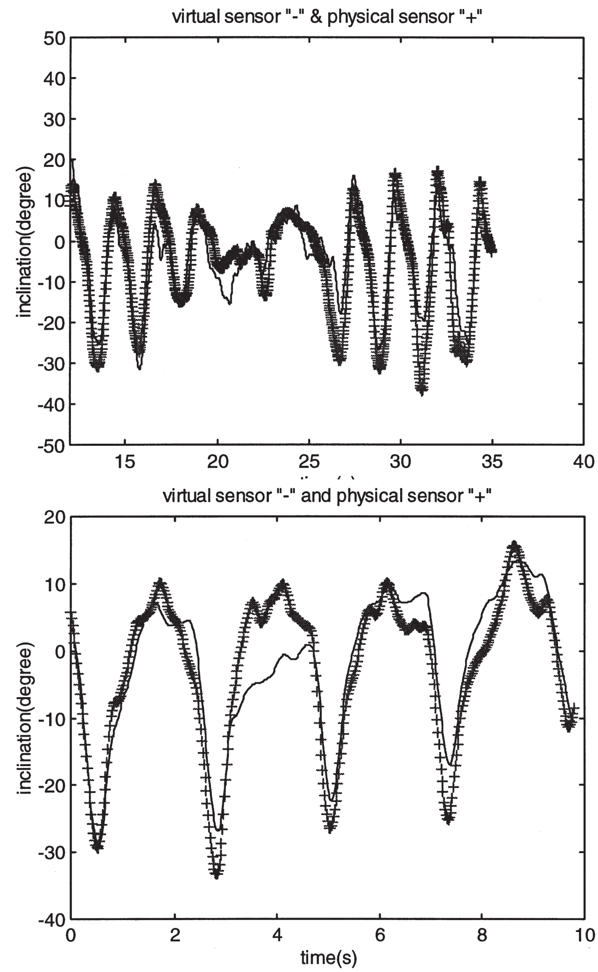


Fig. 4. Evaluation of inclination data on the shank and thigh on the incomplete SCI subject. The signal from Vicon data ‘ − ’ and the signal from gyroscope ‘ + ’ after the low-pass filter are shown. (a) The inclination derived from the gyroscope on the shank and the signal calculated from the motion analysis system. (b) The inclination derived from the gyroscope on the thigh and the signal calculated from the motion analysis system.

This problem was due to the segment being inclined during turning.

Fig. 5 shows how the automatic reset system could correct the drift of shank inclination. The CORRCOEF was 0.97, RMSE was 4.17 degree and NRMSE was 0.30 for the shank inclination from gyroscope and motion analysis system for all four trials.

Fig. 6 shows the effect of using a high-pass filter to correct the drift of the knee angle. The CORRCOEF was 0.98 and RMSE was 3.98 degree and NRMSE was 0.29 for the knee angle derived from two gyroscopes and the signal from the motion analysis system for all four trials.

3.4. Gait analysis

FSRs were used to detect the gait events within the gait cycle and the angular velocities on the shank and

Table 1
Comparison between signals obtained from gyroscope and signals obtained from motion analysis system

Sensor signals	Sensor location	CORRCOEF	RMSE	NRMSE
Angular velocity	Shank	0.94	14.83°/s	0.34
Angular velocity	Thigh	0.91	19.70°/s	0.50
Inclination	Shank	0.92	4.95°	0.35
Inclination	Thigh	0.90	4.99°	0.43
Joint angle	Knee	0.93	6.42°	0.42

The gyroscopes were place on shank and thigh segments, and the derived signals included the angular velocity, inclination and joint angle were compared with the data from Vicon system.

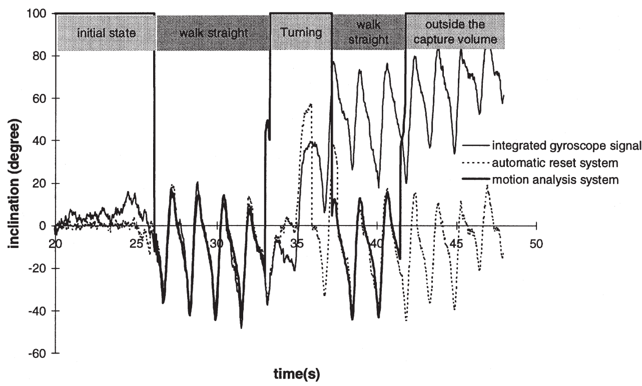


Fig. 5. Shank inclination of a walking trial involving a 180° turn. The thick solid line is the signal calculated from Vicon and the thin solid line is the integrated signal from gyroscopes. The dotted line is the signal of the automatic reset system using force sensors under the foot.

thigh for a normalised gait cycle are shown in Fig. 7. A large positive single-peak was seen during the swing phase on shank signal. On the thigh segment a large positive signal was also seen during the swing phase. However, the angular velocities were more variable during the stance phase.

Knee angle was derived from the angular velocity of these two gyroscopes and is plotted in a normalised gait cycle in Fig. 8.

4. Discussion

The signals from the uni-axial gyroscope showed a good correlation with the signals from the motion analysis system. The signals from the gyroscope on the shank showed a higher correlation to the signals from the motion analysis system than the gyroscope on the thigh.

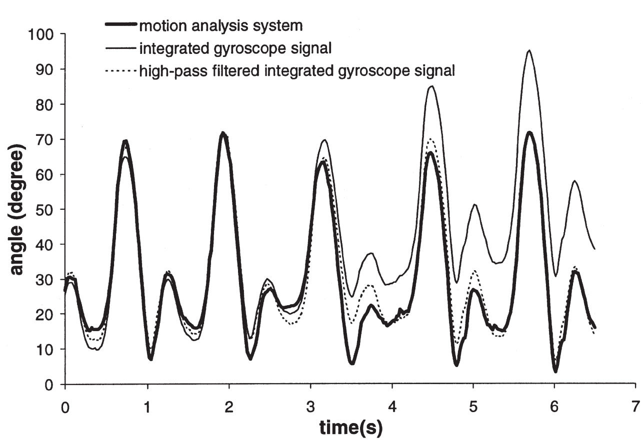
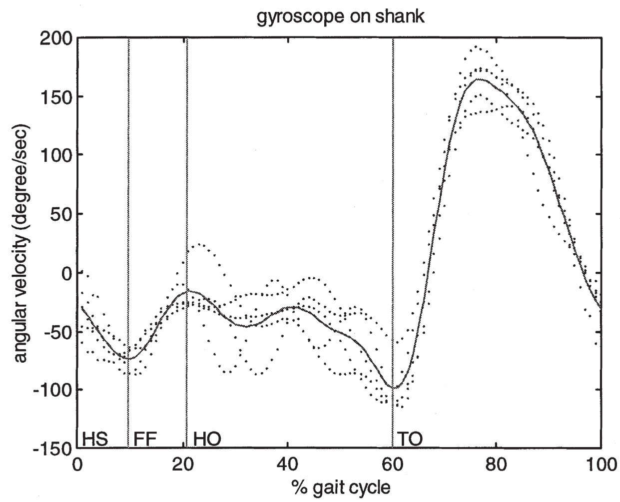
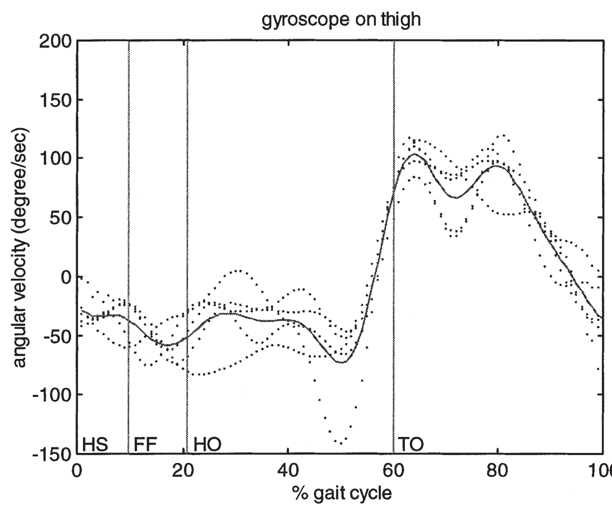


Fig. 6. Knee angle of a walking trial involving a 180° turn. The thick solid line is the calculated signal from Vicon and the thin solid line is the knee angle calculated from gyroscopes on the thigh and shank segments. The dotted line is the knee angle calculated from the integrated signals after filtering with a high-pass filter.



a.



b.

Fig. 7. Shank and thigh gyroscope signals in a normalised gait cycle. The vertical lines mark the heel strike (HS), foot flat (FF), heel off (HO) and toe off (TO). The dotted line is the angular velocity in each gait cycle and the solid line is the average value for angular velocity.

This may be due to the greater amount of skin and muscle movements on the thigh during walking.

Heyn et al. (1996) [13] compared the gyroscope signals with a motion analysis system, but the gyroscopes were fixed on the metal plates which were cumbersome. The metal plates may help to eliminate skin and muscle movements, but a more practical design was preferred for gait analysis and for monitoring daily activities. We have shown that the gyroscope can be easily attached to the skin surface and the measurements have a high degree of accuracy.

The results showed that gyroscopes could be placed anywhere along the same plane on the same segment giving an almost identical signal. The gyroscopes can therefore be attached to a convenient position which might avoid areas of skin and muscle movement.

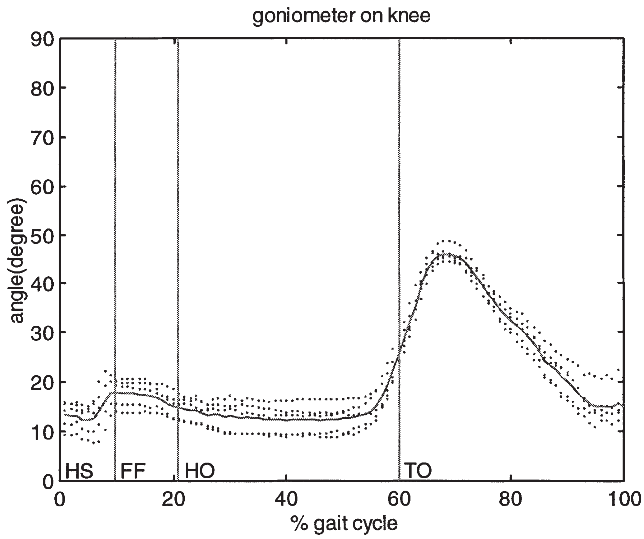


Fig. 8. Knee angle in a normalised gait cycle calculated from the gyroscopes on the shank and thigh segments. The vertical lines mark the heel strike (HS), foot flat (FF), heel off (HO) and toe off (TO). The dotted line is the angle in each gait cycle and the solid line is the average value.

For a practical portable motion analysis system, first it is useful to be able to analyse walking during turning (e.g. walking along a figure-of-eight path) and second it maybe desirable to collect data from several straight line walks without having to reset the system each time the subject changes direction. We have identified that there is a significant problem with the derived signals from gyroscopes if the subject changes direction or turns (Figs. 6 and 7). This is due to the limited information content from the signal of a uni-axial gyroscope. This could have been solved by using a tri-axial gyroscope, however this would have increased the size, complexity and cost of the system. More complex equations are required to calculate the orientation of the segment. The drift problem during turning was removed successfully using either automatic reset in each gait cycle or high-pass filtering. If foot contact information is available from the gait analysis system, then a gyroscope can be automatically reset for every step.

In FES systems, foot switches have commonly been used as the control signals. The foot switch can only detect the foot contact during the stance phase and cannot provide any information during the swing phase. Inclinometers and accelerometers have been introduced to improve the control of FES by providing information during the swing phase. Dai et al. [3] suggested the use of tilt sensors and Willemsen et al. [2] suggested the use of accelerometers for FES control. The results from this study suggest that gyroscopes can be a viable alternative for FES control, capturing information during the swing phase and also providing stance phase information (Fig. 7). However, foot contact is needed to reset the derived signals from gyroscope to prevent drifting.

Systems monitoring daily activity have been designed using accelerometers mounted on different body segments to quantify time spent in standing, sitting and lying [9]. Using gyroscopes, it is possible to discriminate different activities and in addition provide angular information. A system using a single gyroscope on the shank could provide rich information for gait analysis. A high-pass filter to correct any drift and offset, inclination derived from the gyroscope signal could be used to calculate the segment inclination range, cadence and number of steps taken. If the length of the subject's leg is known, then it is possible to estimate the stride length and walking speed (Eqs. (4) and (5)).

$$\text{stride length (m)} \approx \text{segment inclination range (rad)} \times \text{length of the leg (m)} \tag{4}$$

$$\text{speed (m/s)} \approx \text{stride length (m)} \div \text{gait cycle time (s)} \tag{5}$$

The results from the incomplete spinal cord showed the stride length calculated using Eq. (4) was 0.707 m. The stride length calculated from the motion analysis system was 0.695 m. These preliminary results show the possibility of using a single gyroscope on the shank for portable gait analysis.

The angular velocities from gyroscopes can also be used for gait analysis. The pattern of angular velocities on the shank and thigh segments are highly correlated with the gait events on the unimpaired subject (Fig. 7). The pattern on the shank showed two minima, one occurs when foot flat and the other occurs when toe off. There were also two peaks in this pattern. The large one occurred during mid-swing and the small one occurred at heel off. This pattern provides information that can be used to identify different gait events and may be useful for developing control systems.

This paper has focused on the use of gyroscopes for measuring inclination and joint angle of the lower limb. Gyroscopes could be used on other body segments, in particular the pelvis and the trunk, to provide useful information on pathological gait patterns.

The signals from gyroscopes can provide a range of useful information for gait analysis and the signals are highly correlated with the signals from the motion analysis system. Gyroscopes are compact in size and can be easily fixed to the skin, and are therefore suitable for a portable gait analysis system. Data could be collected from these signals using either a portable computer or datalogging device with appropriate interfacing.

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