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# A Comparative Study of Wearable Sensors for Recognition and Analysis of Human Gait

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**ABSTRACT:** Human gait is one of the biometric methods used for identifying humans unobtrusively and from a distance. Gait analysis using wearable sensors is a low-cost, handy and capable way of providing valuable information for many applications. Gait analysis using wearable sensors shows great prospects in biometrics as well as in medical applications. With the development of sensor technology and the analysis method, gait analysis using wearable sensors is expected to play an increasingly important role in biometrics applications. The paper presents a review of the wearable sensors used for recognition and analysis of the human gait.

**KEYWORDS:** biometric, gait recognition, wearable sensors, sensor technology.

## I. INTRODUCTION

Gait analysis is an efficient study of human walking. There are three different approaches for gait recognition and analysis: IP (Image Processing) based, FS (Floor Sensors) based and WS (wearable sensors) based. In IP based gait recognition, subject is identified from the images captured by video. In FS based gait recognition, sensors are placed on the floor. As the subject is walking, his gait can be recognized by these sensors. In WS based gait recognition, devices are worn or attached to the subject's body. The main objective of this paper is to study the sensors used in WS based gait recognition. Tao et. al. [1] Stated that gait can be recognized by different types of motion sensors and systems, such as the accelerometer, gyroscope, magneto resistive sensors, flexible goniometer, Electromagnetic Tracking System (ETS), sensing fabric, force sensor, and sensors for Electromyography (EMG). So by using single or multiple sensors one can able to analyze the gait. Muro-de-la-Herran et. al. [2] further supported that sensors which are used to record gait are force sensors, accelerometers, gyroscopes, extensometers, inclinometers, goniometers, active markers, EMG and these sensors can be placed on various parts of the subject's body.

In this paper, we describe the basic principles and brief overview of wearable sensors which are used in gait recognition. We also provide an analysis of these sensors and the best sensor which researchers can use to record gait. The rest of the paper is organized into 4 sections. Section 2 presents overview of all wearable sensors. Section 3 gives summary of different wearable sensors used by different researchers for their research. Section 4 discusses the best sensor based on previous work that the researcher can choose for his research. Finally conclusion will be presented in section 5.

## II. WEARABLE SENSORS FOR GAIT ANALYSIS

The overview of force Sensors, strain gauges, inclinometers, goniometers, inertial sensors (accelerometers, gyroscope, magneto-resistive sensors), ultrasonic sensor, EMG, ETS, sensing fabric are described in this section.

### A. FORCE SENSOR

This type of sensor can sustain in most environments and can measure force between any two surfaces. In an electrical circuit, this sensor work as sensing resistor. If force or pressure is applied, it may result in change of resistance. While it is unloaded, resistance is high and when sensor comes under the force, it results in decreased resistance. Multi meter can be used to measure resistance and then force could be applied to sensing area. Change in force, applied load, force thresholds are detected by this sensor. Portable electronics, car sensors, musical instruments use this sensor. These

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sensors can be embedded into footwear to measure GRF (Ground Reaction Forces) during the gait recognition. GRF is a 3D vector, which depends on the nature of the interfaces like the foot and the ground [1]. It is used to quantify the power applied on the sensor and will not bother about power applied on all the axes [2]. This type of sensor can be developed by integrating various sensors like piezoelectric, strain gauged and capacitive transducer.

To measure GRF in gait analysis, Hessert et al. [36] designed a wearable force sensor based on a photo elastic tri-axial force transducer. Wang et. al. [37] and Bakalidis et. al. [38] developed force sensors based on a photo elastic tri-axial force transducer to measure GRF in gait analysis. Force sensors can be of various types like capacitive, resistive, piezoelectric and piezoresistive sensors. So sensor can be chosen according to range of pressure it will stand and offers, linearity and sensitivity. In resistive sensors resistance decreases, when the weight placed on them increases. In piezoelectric sensors three deformation meters in three different orthogonal directions are placed with silicone gel. When the pressure is applied, the gel is deformed and this deformation can be calculated by meter. The total pressure can be calculated by deformation meter and gel characteristics. Capacitive sensors changes capacity based upon different parameters. It takes distance between two electrodes into consideration while calculating condenser capacity. Figure 1 shows force sensor. It is mostly used in gait analysis systems. Bae and Tomizuka [50] had developed and embed this type of sensor in shoes as shown in Figure 2.

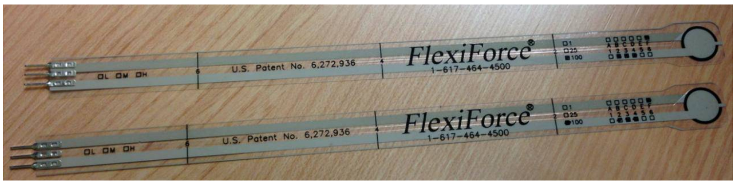

Figure 1: FlexiForce Pressure Sensor [2]

Figure 2: Instrumented Shoe from Smartxa Project: (a) Inertial Measurement Unit; (b) Flexible Goniometer; and (c) Pressure Sensors [2]

### B. STRAIN GAUGE

Strain is how a body bends according to the force. It is fractional change in length. It can be tensile or compressive. As magnitude of strain is very small, it is always measured in micro strain (me) i.e. e x $10^{-6}$. One of the methods to measure strain is a strain gauge which is device whose electrical resistance varies in proportion to the amount of strain in the device. Bonded metallic strain gage is widely used. It consists of fine wire or arranged in terms of grid and it maximizes the quantity of metallic wire. To reduce the effect of shear strain or Poisson strain, the cross-sectional area of the grid in minimized. The grid is bonded to a thin backing, called the carrier. They are mostly used in mechanical engineering research and development to measure the stresses generated by machinery. Aircraft component testing use tiny strain-gauge strips glued to structural members, linkages, and any other critical component of an airframe to measure stress. Strain gauges are typically smaller than a postage stamp, and look as shown in Figure 3.

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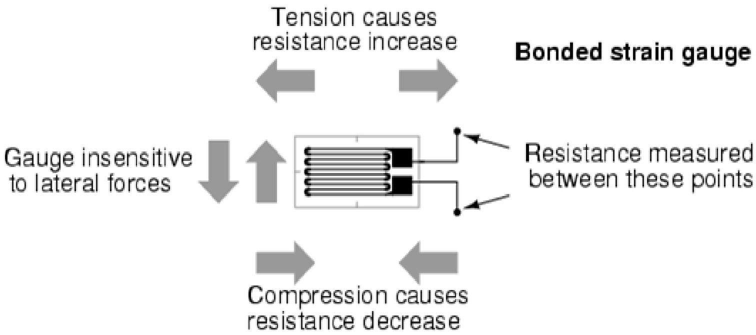


Figure 3: Mechanism of Strain Gauges [21].

Strain gauge is also used for gait recognition. Xue et. al.[3] intended a specialized walker dynamometer system which is based on the multi-channel strain-gauge bridge network and fixed on the walker frame. This system collected the response services between patient's upper extremities and walker during walking process and converted these forces into some morphologic curves of dynamic gait stability in temporal and spatial domains, namely Risk-tendency-graph (RTG). To demonstrate the potential usefulness of RTG, they made a preliminary clinical trial with one male paraplegic patient. The gait stability level of this walking case was quantified from the results of temporal and spatial RTG and relevant unstable phases in gait cycle and dangerous inclinations of patient's body during walking process were also brought forward clearly [26].

### C. INCLINOMETER

By using this device, angles of slope (or tilt) and liking of an object is measured. It is also known as a tilt sensor, tilt meter, tilt indicator, slope alert, slope meter, slope gauge, gradient meter, gradiometer, level gauge, declinometer, pitch and roll indicator or level meter. It is mainly used in different fields such as civil, military, transportation, aviation, government, marine, astrology, aircraft etc. Tilt angle range and number of axes are two main parameters for choosing inclinometer. Tilt angle range is range of desired output which is measured in degrees and it measures both positive and negative slopes by using degrees and percent.

### D. GONIOMETER

A goniometer is also used to measure angle and it is made of plastic and transparent as shown in Figure 4. The two arms which are shown in Figure 4 are stationary arm and moveable arm. Specifically it is use in physical therapy to measure motion around a joint in the body. Physical therapist uses goniometer to measure range of motion around the joint. In order to measure range of motion around the joint, each arm of goniometer is positioned at specific points on the body and the center of the goniometer is aligned at the joint to be measured [6]. In gait analysis flexible goniometer is used which is the combination of strain gauges, mechanical flexible, inductive, and optical fiber goniometers. By using flexible goniometer, relative rotation between two human body segments can be measured and it is operated by measuring change in physical signal which resulting from the angular change.

A number of flexible electrogoniometers based on strain gauge have been developed and used for angle measurement in gait analysis since the 1980s [15,16]. At present, numerous commercialized flexible electrogoniometers are available for the measurement of human posture and spinal motion [17–19]. A mechanical flexible goniometer is designed to obtain angular change by measuring the longitudinal displacement of two parallel wires bent in the plane of rotation, which is demonstrated by measuring the knee joint during human walking [20]. Laskoski et. al. [26] developed a goniometer with an inductive sensor for the measurement of human motion. We can use this sensor to study the angles for ankles, knees, hips and metatarsals. In strain gauge-based goniometers, resistance changes depending on how flexed the sensor is. So when the sensor is flexed, its resistance increases proportionally to the flex angle. Dominguez et al. [46] developed a digital goniometer based on encoders to measure knee joint position.

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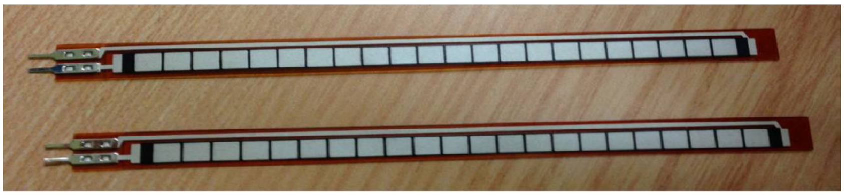

Figure 4: Flexible Goniometer [2].

### E. INERTIAL SENSORS

Inertial sensors are combination of accelerometers, gyroscopes and sometimes magnetometers which are used to measure object's velocity, acceleration, orientation and gravitational forces.

#### 1. ACCLEROMETER

An accelerometer works based upon Newton's laws of motion i.e. acceleration of a body is proportional to the net force acting on the body. An accelerometer measures acceleration along its sensitive axis. It works on the principal of mechanical sensing element that comprises proof mass attached to mechanical suspension system with respect to a reference frame. So acceleration and angular velocity can be obtained by 3-axis accelerometers and gyroscopes and by using this velocity, flexion angle can be obtained. Thus, to extract the number of steps taken in a determined time lapse, researcher has to analyze the signals from the accelerometers and applying filtering as well as classifying algorithms. This type of sensors may be fitted within an IMU device (Inertial Measurement Unit).

There are three types of accelerometers mainly used piezoelectric, piezoresistive, and capacitive accelerometers [5]. Piezoresistive and capacitive accelerometers can provide dual acceleration components and have higher stability. Thus, these types of accelerometers are suitable for measuring the motion status in the human gait [6]. By attaching these accelerometers to the feet or legs, the acceleration of the feet or legs in the gait can be determined to perform the gait analysis [7]. Now-a-days accelerometer is incorporated in smart phones and it is used to measure the device's orientation – tilt, landscape or portrait. Actually a smart device with accelerometer is nothing but a circuit based on MEMS (Micro Electro Mechanical System), that senses or measures the forces of acceleration that may be caused due to gravity of movement or tilting action. So, it is a device to measure the speed of acceleration or movement to which it is attached. If it is employed in mobile, it will do accordingly. It also senses the angle at which it is being held via mobile.

#### 2. GYROSCOPES

It measures the spin movement of the device. The gyroscope is a sensor that can provide orientation information with greater precision. Android's Photo Sphere camera feature can tell how much a phone has been rotated and in which direction by using this sensor. It is also used by Google's Sky Map for telling what constellation you're pointing a phone at. A gyroscope is a device for measuring or maintaining orientation, based on the principles of angular momentum. So we can assume a gyroscope as a spinning wheel or disk and orientation of gyroscope does not remain fixed. It returns three-dimensional values just like accelerometer. It returns angular velocity i.e. how fast the device rotates around the axes. Gyroscope detects roll, pitch and yaw of our smart phone.

The gyroscope must always face the same direction, being used as a reference to detect changes in direction [2]. Gyroscopes can be available based on different principles such as electronic, microchip packaged MEMS, solid-state ring lasers, fiber optic, quantum. A gyroscope can be applied for the measurement of the motion and posture of the human segment in gait analysis by measuring the angular rate [8-10]. For example, to find angular velocity or an angle of feet, gyroscope can be attached to the legs of human and to record gait of subject, accelerometer can be embed with gyroscope.

#### 3. MAGNETORESISTIVE SENSOR

It is based on the magneto resistive effect as shown in Figure 5. If a magnetic flux is applied, a Lorentz force relative to the magnetic flux mass will deflect the current path and if a magnetic flux is not applied the current flows straight through the InSb plate. As the current path is deflected, the current flows through the plate for a longer distance. That

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is, the magneto resistive effect refers to the change in the resistivity of a current from a magnetic field, with the resistance change proportional to the tilt angle in relation to the magnetic field direction [11]. Based on this magneto resistive effect, magneto resistive sensors can estimate changes in the orientation of a body segment in relation to the magnetic North or the vertical axis in the gait analysis [12-14]. Such sensors can provide information that cannot be determined by accelerometers or the integration of gyroscope signals.

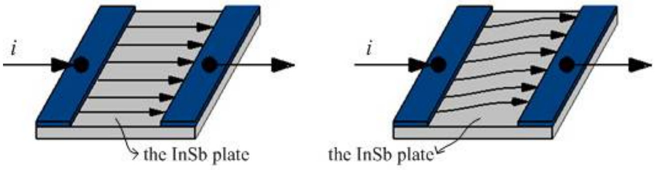


Figure 5: The Model of Magneto Resistive Effect. (a) Current Mode under Non-Magnetic Field; (b) Current Mode under Magnetic Field [1].

Sensor which is widely used in gait analysis is IMU (Inertial Measurement Units). Anna et al. [42] designed a system with inertial sensors to quantify gait symmetry and gait normality, and they evaluated it against clinical assessments for hip replacement patients and they were able to get a good correlation factor. Tay et al. [45] presented a system with two integrated sensors located at each ankle position to track gait movements and a body sensor positioned near the cervical vertebra to monitor body posture. The system was also able to measure parameters such as maximum acceleration of the patients during standing up, and the time it takes from sit to stand. The miniaturization of inertial sensors allows the possibility of integrating them on instrumented insoles for gait analysis, such as the Veristride insoles developed by Bamberg et al. [47] , which additionally include specially designed pressure sensors for distributed plantar force sensing, Bluetooth communication modules and an inductive charging system as shown in Figure 6. These sensors are usually fitted in instrumented shoes to measures ankle to foot angles.

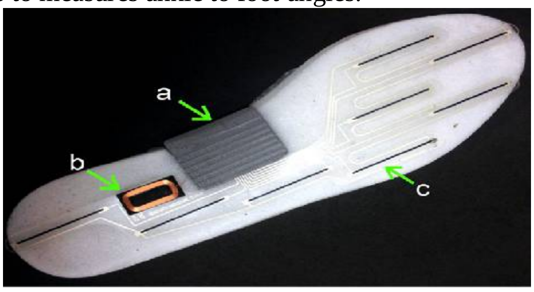


Figure 6: Instrumented Insole: (a) Inertial Sensor, Bluetooth, Microcontroller and Battery Module; (b) Coil for Inductive Recharging; and (c) Pressure Sensors [2]

### F. ULTRASONIC SENSORS

Ultrasonic sensors are used to measure short step, stride length and separate distance between feet. This sensor can measure the time wave takes to send and receive and the speed at which sound travels through the air. So by obtaining the time and speed we can get distance between two points. The measurement range varies between 1.7 cm and nearly 450 cm. we can also use this sensor to obtain distance between the foot and the floor.

### G. ELECTROMYOGRAPHY (EMG)

The EMG is electrical exhibition of either voluntary or involuntary muscle retrenchment. We can get the EMG signal from the subject unobtrusively with surface electrodes as shown in Figure 7. The measurement of EMG is very small due to composite analog signal. According to [48] surface electromyography (SEMG) is useful in unobtrusive assessment of simillar pathophysiological mechanisms potentially hindering the gait function such as changes in passive muscle-tendon properties (peripheral, non-neural component), paresis, spasticity, and loss of selectivity of motor output in functionally antagonist muscles. Furthermore, EMG signals can be used to measure different gait characteristics. Kinematic plots of joint angular motion can be compared to the EMG plots recorded at the same time to see if one set of data can explain the other, the amplitude of EMG signals derived during gait may be interpreted as a

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measure of relative muscle tension and it has been found that the EMG amplitude increases with increased walking speed and that the EMG activity is minimized with subjects walking at a comfortable speed.

In a study performed by Wentink et al [49] demonstrated that EMG measured at a prosthetic leg can be used for prediction of gait initiation when the prosthetic leg is leading, predicting initial movement up to 138ms in advance in comparison to inertial sensors.

Figure 7: Wireless EMG/EEG/ECG System [2]

EMG was developed by [1] to perform an oblique measurement of force action using surface or wire electrodes and to quantify force action in lower boundary in a human gait. These electrodes are sensors for EMG and used to identify voltage to offer details of timing and intensity of force reduction and commercially use in conjunction with wireless technology as shown in Figure 8. So, EMG sensors can be used to understand the assessment of force activity in human gait and help an important task in evaluating the walking performance of individuals with problems in their lower extremities [39-41].

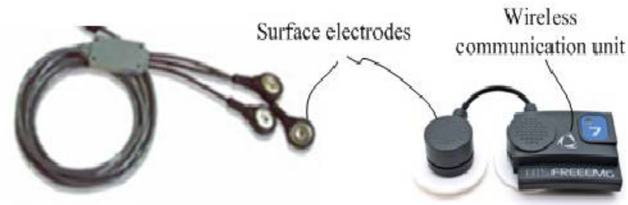


Figure 8: Commercialized Wireless EMG Sensors. The wireless EMG sensors include the electrodes and wireless communication unit [1]

### H. ELECTROMAGNETIC TRACKING SYSTEM (ETS)

ETS is a device which works on Faraday's law of magnetic induction. When a subject carries this sensor, the induced voltages of the sensor coil will vary with change in subject's position and orientation, due to the movement performed inside magnetic fields. These magnetic fields are generated by a fixed transmitter. So by using this sensor, the positions and orientations of the subject in relation to the transmitter can be calculated. ETSs had been applied in bioengineering and gait analysis by [24, 25].

### I. SENSING FABRIC

It is a combination of sensing technology and fabric, which ranges from very apparently attached electronic components to a replacement of fibers and yarns with sensing properties inserted in normal fabrics, to electronic components made of fabric materials. This sensor is more stretchy and easy to measure subject position as well as movement as compare to other wearable sensors. For sensing fabric, the sensing properties can be achieved by applying piezoresistive, piezoelectric or piezocapacitive materials. As coatings, different polymeric material can be used depend upon sensing property for particular purpose. [33-35] had used printing carbon polymers onto stretchable fabrics, such as Lycra for a perfect sensing fabric.

## III. ANALYSIS OF COMPARISON OF WS SYSTEM

As devices are worn by the subject in wearable sensors, it is easy to evaluate gait during daily activities of the subject outside the lab. So it is the cheaper solution to record gait. Nowadays most promising and widely used wearable sensor is inertial sensor as it is combination of accelerometer, gyroscope and magneto resistive sensor [2]. Novak et al. [28]

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have developed a system based on inertial and pressure sensors to predict gait initiation and termination. They demonstrated that both types of sensors allow timely and accurate detection of gait initiation, with overall good performance in subject-independent cross-validation, whereas inertial measurement units are generally superior to pressure sensors in predicting gait termination. They had developed various sensors for gait phase identification, which include foot switches, force sensitive resistors (FSRs), accelerometers, pendulum resistors and goniometers.

One of the first foot sensors proposed was a heel switch which detected heel strike during normal gait. None of the above mentioned sensors achieved results with accuracy greater than 95%. Inertial sensors can be used to estimate walking speed by various methods, which are described in the review by Yang and Li [29]. As inertial sensors have been integrated in commercial mobile devices, a wide range of applications that use them to offer simple inexpensive gait analysis systems have appeared for use in fields such as telemedicine and telerehabilitation [30]. Kashihara et al. [31] and Susi et al.'s [32] worked on motion mode recognition and step detection. They reported that mobile devices are widely used for recognition of gait. Consequently, Popovic, et.al [43] proposed a gait identification sensor with three FSRs, an inclinometer and a rule-based observer. This sensor detected heel-off, swing phase, heel strike and mid stance with an accuracy greater than 99%. So one can use wearable sensors based on their requirement and parameters. Different sensors used by different authors for their research is shown in Table 1.

Table 1: Sensors used in Existing Studies for Gait recognition

| **Contributed by** | **Research paper title** | **Sensor used** | **Techniques used** |
|---|---|---|---|
| Smidt et. al. [4] | An automated accelerometry system for gait analysis | Accelerometer | - |
| Bouten et. al. [6] | A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity | Accelerometer | - |
| Birsel and Billur [8] | Leg motion classification with artificial neural networks using wavelet-based features of gyroscope signals | Gyroscope | DWT decomposition for signal extraction and ANNs for leg motion classification |
| Catalfamo et. al. [9] | Gait event detection on level ground and incline walking using a rate gyroscope | Gyroscope | Reference pressure measurement system for comparison of performance Histogram |
| Tuncel et. al. [10] | Classifying human leg motions with uniaxial piezoelectric gyroscopes | Uniaxial piezoelectric Gyroscope | Comparison of BDM, RBA, LSM, k-NN, DTW, SVM, ANN Techniques |
| Sato. et. al. [19] | Goniometer crosstalk compensation for knee joint applications. Sensors | Goniometer | RMS(Root Mean Square) |
| Willemsen et. al. [27] | Real-time gait assessment utilizing a new way of accelerometry | 2 1-D Accelerometers | Low pass filtering |
| Yang and Li[29] | Inertial sensor-based methods in walking speed estimation: A systematic review | Inertial sensors (accelerometers and gyroscopes) | - |
| Bamberg and Benbasat [47] | Gait analysis using a shoe-integrated wireless sensor system | 3 Orthogonal Accelerometers, 3 Orthogonal 4 force sensors, 2 Bidirectional bend sensors, Electric field | - |

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| | | | |
|---|---|---|---|
| | | height sensor | |
| Dias et. al. [51] | Extracting gait parameters from raw electronic walkway data | Accelerometers | - |
| Nowlan [52] | Human Identification via Gait Recognition Using Accelerometer Gyro Forces | A single sensor composed of accelerometer and gyroscope | - |
| Sprager and Zazula [22] | Gait identification using cumulants of accelerometer data | Accelerometer | SVM, PCA |
| Chan et. al. [23] | Feasibility study on iPhone accelerometer for gait detection | Accelerometer | - |

## IV. ACCLEROMETER

Smart mobile phones, now-a-days mostly embed with MEMS accelerometers and gyroscopes to find out device orientation, provide developers and users with a wealthy and easy accessible stage for discovery. Ample of application programs were developed based on smart phone sensors. Dias et. al. [51] discussed in their work that accelerometers are capable of recording high frequency raw data which prove it to be valuable tools for assessment of gait parameters during daily activities. Smidt et. al.[4] suggested that an accelerometer is a handy measuring device used for gait analysis by a newly devised plan because of its capability to detect the characteristics of an entire movement. Moreover Willemsen et. al.[27] suggested that installation of an accelerometer in gait analysis depends on the purpose of its implementations because accelerometer have been attached to the different parts of body such as thigh, foot, heel, to measure acceleration of a specific part such as joint.

Nowlan [52] in his research discussed that the accelerometer is increasingly embedded in cellular phones. Moreover these devices are small enough to fit in a pocket and the device communicates via bluetooth with a remote station, which carries out the calculation. So the device must be carried by the subject generally in the pocket of the pants. Sprager and Zazula [22] stated that accelerometer can measure accelerations up to three different directions. They paid particular attention to the position of the accelerometer. They concluded that the small difference in orientation and phone position, related to the subject’s hip, does not influence the accelerometer signal significantly. However, they kept same placement and direction of the cell phone for each subject. Different placements of the device on the same subject would lead to completely various recognition of subject's walk. The results found by Chan et. al. [23] proved that it is possible to extract features from the accelerometer of an iPhone such as step detection, stride time and cadence.

## V. CONCLUSION

Gait analysis using wearable sensors provide quantitative and repeatable results over extended time periods with low cost and good portability showing better prediction and making great progress in recent years. At present, commercialized wearable sensors have been adopted in various applications of gait analysis. Wearable sensors used for gait recognition are studied and a summary of different wearable sensors used by different researchers is given. As a result, a researcher can use different wearable sensor for his research based on criteria or component of his research. An accelerometer is a handy tool, which can be attached to different parts of body, already embedded in portable devices, small enough to fit in pocket, able to communicate with Bluetooth, measure acceleration in 3 different directions, calibrated by gravity, able to extract features such as step detection, stride time, cadence, so as a result the researcher can choose it as the best sensor.

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