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Sensor Technologies for Foot Clearance Measurement

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ABSTRACT: *The study of lower limb trajectory during walking involves many measurements including spatial and temporal parameters. Among the whole range of measurements, the spatial parameters of the foot during the swing phase of the gait cycle, the distance of shoe sole about the ground (or foot clearance) has been identified as a vital gait parameter. Foot clearance during swing phase directly influences the risk of fall among the elderly. The foot clearance also plays a significant role in diagnosis and assessing the treatment process in several neurological disorders, mainly Parkinson's disease (PD). With the advent of MEMS-based sensors, the real-time measurement of foot clearance is made possible, and enormous research is going around. In the present paper, five different foot clearance measurement techniques were studied and compared. The primary intention of the study is to choose an appropriate sensor for assessment of gait, which meets low cost, reliable, real-time, and out-door measurement capabilities. It was found that a triaxial accelerometer is the best choice for foot clearance measurement apart from many other measurements that can be made with the same sensor.*

KEYWORDS: *Foot clearance, gait analysis, Tri-axial accelerometer, Ultrasonic distance measurement, Microwave Doppler, Electric field sensing, Infra-red distance measurement.*

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I. INTRODUCTION

Gait refers to the manner by which a person moves his entire body from one place to another. Gait cycle is the sequence of events occurring between two successive heel contacts of the same foot (1). The gait cycle can be classified into two major phases namely stance and swing. Stance occurs when the foot is in contact with the ground and swing refers to the phase when the foot is off the ground. We are interested in the measurement of the vertical distance between the heel and the ground during the swing phase of the gait cycle and is referred as foot-clearance. It is found that the trajectory of the foot during swing phase is the most critical event that can initiate the possibility of trip-related falls in older adults and also in patients with neurological disorders, such as in PD.

The current practice in measuring foot clearance mostly requires laboratory setting with the use of reflective or active markers, one or more video cameras, thread-mill or suitable floor and dedicated computer software running on suitable computers (2). This type of foot clearance measurement may not be representative of real-life analysis in natural settings, such as at home or outdoor. Even in a laboratory environment, the problems associated are marker slippage, marker misidentification, marker hiding, etc. (3). Systems using Marker-based technologies provide information for a limited number of gait cycles and could be used only in a closed environment. Due to the apparent limitations, newer systems are under research. The functional requirements of the devices, for gait analysis, need to be:

1) Must not affect gait
2) Long-term monitoring
3) Characterize the motion of both feet
4) Un-tethered
5) Allow the subject to use his or her own shoes.

II. AVAILABLE TECHNIQUES

Distance measurement techniques are numerous, however, due to their characteristics; each poses limitations that can affect gait measurement. The first requirement is the most important, in order not to cause any changes in gait. Accordingly, the hardware had to be compact, lightweight and small. Keeping in view of the above requirements, after careful scrutiny of literature the following transducers were found to be acceptable and considered for further evaluation.

a) Ultrasonic distance Measurements
b) IR based distance Measurement
c) Microwave Doppler Radar
d) Electric field sensor and
e) Accelerometer based Measurement

In the present paper, these techniques are studied and the results are compared.

2.1. Ultrasonic distance measurement

The application of ultrasound for distance measurement principle is basically the same as that used in SONAR. The only difference is the speed of measurement, due to a transmission medium difference. Several techniques of distance measurement using ultrasonic systems were proposed in the literature. These include Time-Of-Flight (TOF), Continuous wave phase shift method, a combination of TOF and phase shift and also Doppler velocity measurement (4).

2.2. IR based distance measurement

IR sensors are extensively used as an obstacle detector for robot applications; the same can be extended for distance measurement provided the reflection characteristics of the surface is known. The distance measuring unit consists of an IR LED and IR sensor. The IR sensor detects the IR radiation reflected from the obstacle, originally generated by IR LED. The output voltage level of the IR sensor depends upon the intensity of IR radiation received by the sensor. The intensity, in turn, depends on the distance between the sensor module and obstacle, provided the IR LED produces a constant intensity (7).

2.3. Microwave Doppler Radar

Microwave Doppler Radar sensor can detect motion or speed of moving objects through Doppler principle. It transmits a 10.5 GHz microwave frequency electromagnetic signal and waits for the signal to receive back and monitor the shift in frequency of the received signal. The frequency deviation resulted due to the motion of the object is converted into distance. J. L. Geisheime, et.al (6) has exploited this principle to measure the motion of the subject. The equipment presented in this paper is too heavy and cannot be implemented for foot-clearance measurement. With the advent of latest technology, the miniaturization of electronic circuits was made possible and the foot-clearance measurement was also possible.

2.4. Electric Field Sensor

This technique involves electric field sensing between two plates of a capacitor, namely sensing electrode and the ground electrode. The sensing electrode is excited by a high-frequency sinusoidal AC voltage source. The ground electrode is connected to the ground of the circuitry. As the distance between the sensing electrode and ground is varied, the measured capacitance is also varied. This capacitance variation is converted into a voltage signal. The Motorola Company has designed a dedicated IC (MC33794 DH) for this application and is commercially available (4).

2.5. Accelerometer based measurement

Accelerometers were first conceived to monitor the motion of human movement as early as the 1950s (5), but due to their expensive and bulky state were deemed unsuitable for this purpose during that period. With the advent of the MEMS-based triaxial accelerometer, the present-day trend is to use this sensor, for movement-related measurements. The application range extends from gait to posture measurements and also to measure tremor.

III. DEVICE COMPONENTS AND DESIGN

All the sensors considered for the application are procured and calibrated. All the sensors are then fixed on the distal end of the foot-ware in parallel to the calcaneus bone (heel) of the foot as shown in the Fig.1. As the four sensors, except for ultrasonic sensor provide an analog output, the outputs from all these four sensors are fed to a 10-bit ADC, built into the microcontroller (PIC 16F877A). The ultrasonic sensor provides a positive pulse, whose width is proportional to the foot clearance. The microcontroller is programmed to sample all the analog signals for every 2msecs and also measures the pulse width output from the ultrasonic sensor. To maintain the sampling accuracy, the timer is programmed to provide an interrupt for every 2msecs. The sampled data is serially fed to a Blue tooth module so that the data is transmitted to a PC, which is also interfaced to a Blue-tooth module. The block diagram representation of the whole set-up is as shown in the Fig.2. In PC the actual analysis of data takes place.

Fig.1. Footwear consisting of five sensors at the backside

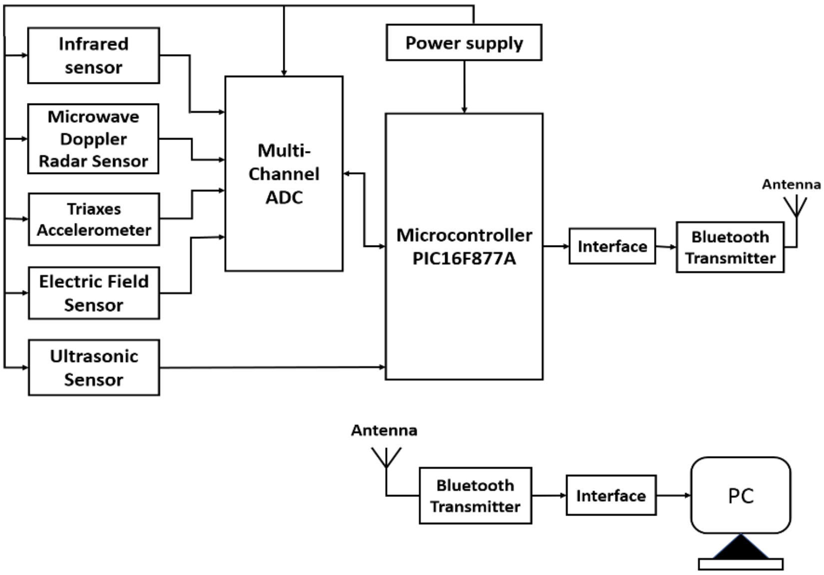

Fig.2. Block diagram representing the setup

IV. METHODOLOGY

For our analysis, we have recruited five healthy adult male subjects. The subjects were explained about the study, and written consent is obtained from each subject. For our research, we have not recruited the neurological patients, as the weight of the whole set up is high, it may further impair the gait pattern of the patients. Each subject is asked to wear the footwear and asked to walk at their comfortable pace for 10 meters. As the subject is walking all the parameters are calculated by PC. Except for accelerometer, all the other signals directly provide the foot clearance. When it comes to the accelerometer, the signal has to be adjusted for gravitational forces and then integrated twice to get the desired parameter, i.e. foot clearance. The obtained data is plotted and is shown in fig. 3.

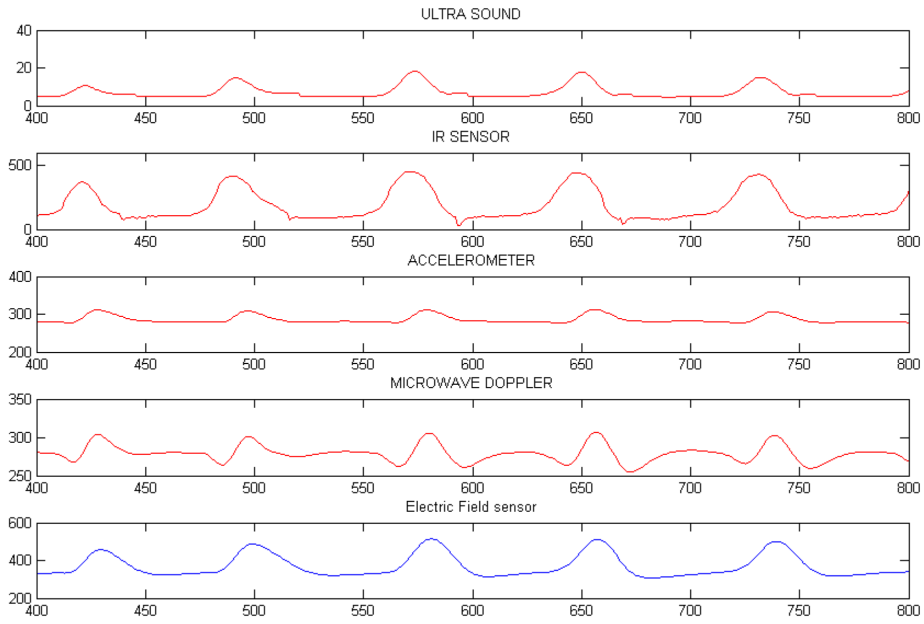

Fig. 3: Foot clearance measurements obtained from different sensors

V. RESULTS AND CONCLUSIONS

Table 1 shows the comparison of the five measurement techniques data obtained from five subjects. It indicates the maximum foot clearance obtained from the waveforms manually.

Table 1: Comparision of data obtained from five sensors

Sl. No	Ultrasound (in cm)	IR Sensor (in cm)	Accelerometer (in cm)	Microwave Doppler (in cm)	Electric Field Sensor (in cm)
1	2.54	2.58	2.55	2.67	2.50
2	1.78	1.72	1.76	1.82	1.71
3	2.31	2.35	2.32	2.42	2.20
4	2.43	2.49	2.39	2.51	2.38
5	1.95	2.02	1.99	2.05	1.93

From the results, it is quite evident that more or less all the sensors are giving the same output, except for a minute static error, which is more or less constant.

When it comes to the foot clearance trajectory during the stride phase, IR sensor is providing even minute variations in the foot height. With ultrasound, during heel off the foot clearance is high, as the ultrasound beam is projected with an angle onto the floor. In case of microwave also, it is same as that of ultrasound. Electric field sensor is very accurate, and the sensor is embedded in the sole of the footwear. With an accelerometer, the main problem is drift due to environmental factors. The other problem, being the double integration, which accumulates the error as the time is passing on. There should be provision to make this accumulated error to zero at the end of each step during the walking cycle.

When it comes to power consumption, the microwave Doppler consumes maximum power, and the placement of the sensor also poses a problem, as the size of the transducer is large. Next comes the ultrasound system. The least power consuming device is an Electric field sensor. Whereas the accelerometer also consumes less power. The electric field sensor, though it is consuming less power and producing accurate measurements when two sensors are mounted on both feet, it provides a cross coupling. Thus, the sensor can be used either with the left or right foot, but not on both the feet.

Finally, the accelerometer sensor is recommended, though it is having the problem of drift and integration related errors. The main reseason is the triaxial accelerometer can provide data relating to stride length and also tremor or deviations from the normal course of the foot, especially useful in studying PD cases. The other advantage with the triaxial accelerometer is that it can be mounted on both the shoes and also on distal and frontal ends of the foot, which can be used to study the drop foot problem.

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