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A review of smart technologies embedded in shoes

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Abstract Advancement in wearable devices, with many new inventions and development in technology, has revolutionized smart shoe technology. These smart shoes sometimes referred to as intelligent shoes or computer-based shoes. Some of the smart shoes are also capable of recognizing and recording the day-to-day activities of the user. Such smart shoes are designed with sensors, vibrating motors, GPS, wireless systems, and various other sensors/actuators for the comfort and convenience of the shoe user. In the current manuscript, we have reviewed various technologies that are being implemented in smart shoes.

Keywords Smart shoes · Pedometer · Smart footwear · Energy harvesting · Gait analysis

1 Introduction

Smart shoe is a modified ordinary shoe with high-tech features, such as recording [4] bio-metric data and activities of the user, auto-adjust size for comfort fitting. For a few smart shoes, the data is available to the user via the app. These apps also sometimes send out suggestions on, how one can improve, the lifestyle towards healthy living. Various technologies like sensors, motors, accelerometer, Bluetooth, etc. are being implemented in the design of regular footwear, and hence turn them into a smart shoe. With the new inventions in technology coming up every day, numerous features are being added to the smart shoes. Smart shoes are sometimes used to help visually impaired people to navigate their destination with the help of GPS tracker. Figure 1 shows an overview of smart shoe technologies. Smart shoes are divided into three main categories which are electro-mechanical smart shoes, mechanical smart shoes, and electronic smart shoes. The mechanical smart shoes

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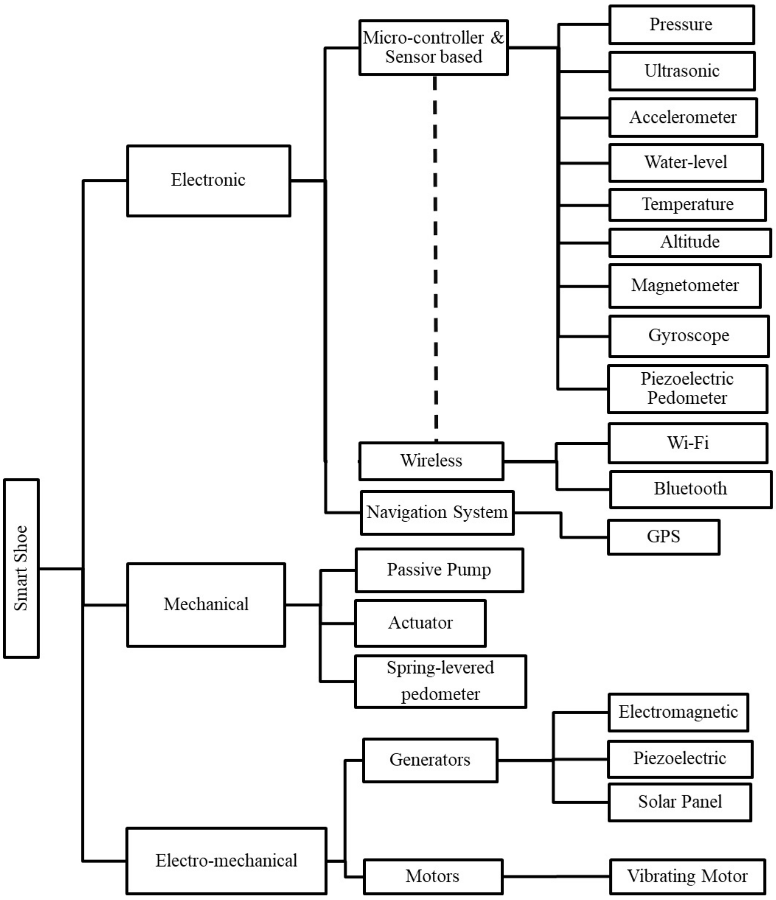

Fig. 1 Overview of smart shoe technology. There are three main types of smart shoes, viz. Electronic, Mechanical and Electro-mechanical smart shoes.

are further divided as Passive pump bases smart shoes, actuator based smart shoes, and spring-levered pedometer-based smart shoes. The electromechanical smart shoes are of two types. The first one is the generator embedded into the smart shoes [5]. These generators could be electromagnetic, piezoelectric, or solar panel-based. The second type of electromechanical smart shoe is motors induced inside a smart shoe to give a mechanical vibration. Those shoes have vibrating motors connected to the smart shoes. Under Electronic sensor-based smart shoes, we have two main ways of connectivity which are wireless connectivity and wired connectivity. It is always preferred to have wireless connectivity with WiFi or Bluetooth [6] rather than the traditional wired connectivity. Wired smart shoes allow the user to get all the data at the end of the day to dump in the pc or laptop. Different sensors integrated with smart shoes are:

– Pressure sensor: It measures foot pressure, This kind of shoes is typically used by diabetic patients.

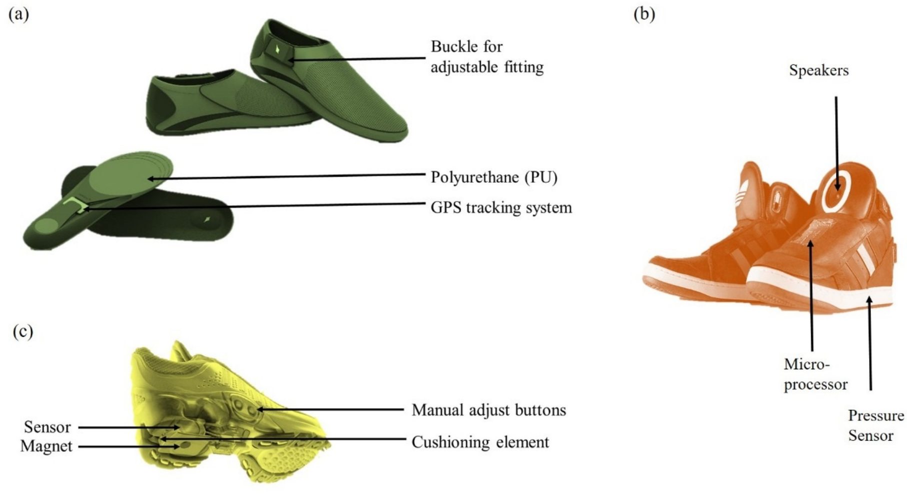

Fig. 2 Interactive smart shoes (a) Lechal Shoes that navigate using GPS. [1] (b) Google shoes that can talk with the user and also measures pressure. [2] (c) Adidas Micropacer smart shoes provide comfort cushioning. Micropacer can also measure the runner's distance traveled, speed, and calorie consumption.[3]

- Ultrasonic sensor: It is used to measure the distance to object. Objects proximity can be sensed using this sensor. Mostly used by blind people.
- Accelerometer sensor: It is used to track down the movements and needed in gait analysis [7].
- Water level sensor: These sensors are typically used by fire-fighters when they have to go to unknown scenarios with different water levels, where the depth of the water level is unknown.
- Temperature sensor: This is mostly used to measure the body temperature and sometimes it can also measure the atmospheric temperature. Mostly used by people in cold countries.
- Altitude sensor: An altitude sensor is used by the climbers or trekkers when they go at high altitudes and specially used by anemic patients, the smart shoes help them receive an early warning.
- Magnetometer sensor: Magnetometer sensor is equipment that is capable of detecting the strength and direction of the magnetic flux at a selected place [8].
- Gyroscopic sensor: This sensor is used to track down the angular movement hence it is important for gait analysis, to see that both legs are landing at the anti-symmetric angle and also help to determine walking patterns or the severity twist in the feet can be measured [9].
- Piezo-electric pedometer: It is used to count the number of steps that the user walked during a specific time.

2 History of smart shos

In the mid-1980s, two new technologies were introduced shoes. The first one could measure the distance, average speed, and calories consumed of an athlete while the other was a computer-based shoe with a build-in pedometer that could track the distance and traveled by the user and calories burnt. Calories burnt per mile is calculated in Pedometer as follows:

$$Calories\ burnt/mile = 0.57X(weight\ in\ lbs.) \quad (1)$$

With technology taking over the shoe industry, the leading giants of the footwear started implementing the same within their companies. In 1984, Adidas announced 'Micropacer' which became a technological breakthrough in the world for running shoes. Its technological integration was so unique, that it instantly became a hit among consumers. This was the first electronic based smart shoe ever introduced that could measure the runner's distance, average speed, and calorie consumption with the capability of saving the total route covered by the runner. In celebration for its 30th Anniversary in 2014, Adidas re-released revolutionary 'Micropacer' (fig. 2 (c)). In 1985, Puma came up with the build-in pedometer technology that could read that data on Apple IIe or Commodore 64 computers. In the early 1990s, flashing lights in heels shoe was trending the market. The LA Gear compony brought up the idea for lights in the shoe for the very first time.

3 Electronic smart shoes

While the leading companies kept up with the trends for the footwear, various innovations in the medical field [14] have also been seen. A smart shoe for people who are visually impaired or physically challenged has also been established. As shown in figure 2 (A), Bluetooth enables a shoe called 'Lechal' (which means 'take me there' in Hindi) sync up with the smartphone app that uses Google Maps and guides the wearer to take a turn accordingly to reach the desired destination was developed by Indian startup company 'Ducere Technologies Pvt. Ltd.'

Further, with the advancement in science and hi-tech these companies starting bringing supplementary fashions as per the shoppers' comfort and taste. In 2005, Adidas launched the first intelligent shoe called Adidas-1 that provided 'intelligent cushioning' by self-adjusting itself using a sensor and a magnet. The microprocessor used in the shoe was capable of making 5 million calculations per second. In December 2004, MIT's spin-off company VectraSense presented a new computerized shoe name 'Verb for the shoe'. This footwear was skilled for sensing the user's activity level and automatically adjust itself to improve comfort and performance. The shoes were designed through an embedded computer that could learn the patterns and adjust the fitting according to the comfort of the user. The processor also allowed a wireless link for data storage and information sharing. The massive breakthrough was seen when Google invented in 'talking shoes' that could commune between the man and the 'Google talking shoe' (fig. 2 (b)).

Figure 3 (b) shows, a novel approach, to measure the temperature, pressure, and humidity across the foot to prevent foot ulceration is taken into consideration using 8 hotspots. First hotspot is attached at the big toe and second hotspot at the third toe tthen next three hotspots are across the ball of the foot, two

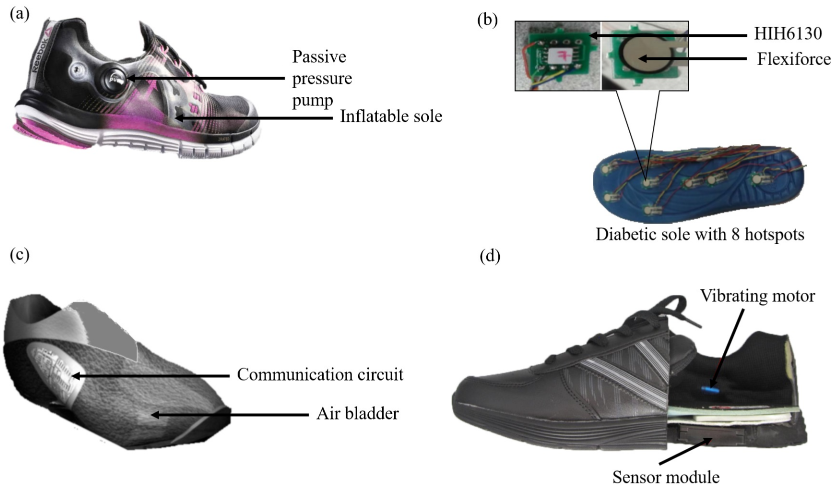

Fig. 3 Mechanical and sensor-based smart shoes.(a) Reebok Z-pump fusion comes integrated with a mechanical passive pressure pump. It inflates sole such that fits comfortably to the user. [10] (b) Diabetic shoes use HIH6130 and flex force sensors [11](c) MIT developed verb for shoes that uses air bladder for comfort fitting. Shoe can communicate with smartphones. [12] (d) Foot progression angle shoes which use a sensor module and vibrator to provide real-time vibration feedback.[13]

hotspots in the arch, and one hotspot at the heel of a typical human foot that can be monitored. The insole of the shoes is embedded with sensors that are PCB mounted with HIH630 facing up and FlexiForce facing down on the insole of the shoes. The smart shoe contains sensors that obtain readings for parameters such as temperature, humidity, and pressure via each of the hotspots. It can measure a wider range of temperatures from -25^{o} to 85^{o} Celsius and humidity from 0 to 100 %. The data is then sent through an attached Bluetooth radio to a smartphone that displays the data on an app for self-monitoring. The app then sends an alarm as soon as a considerably large difference is received for any of the parameters at two or more hotspots. The data is then sent over the wireless network that is LAN or WAN to a central server, where further processing and interpretation is done. The goal is to make this information accessible to health officials for diagnosis and monitoring.

Figure 3 (c) shows, MIT's spin-off company VectraSense presented a new computerized shoe named 'Verb for Shoe'. This footwear was skilled for sensing the user's activity level and automatically adjusting itself to improve comfort and performance. The shoes were integrated with embedded computer that could learn the patterns and adjust the fitting according to the comfort of the user via the air bladder technology. The processor also allowed a wireless link for data storage and information sharing. The fashion-forward shoe not only provides computerized shoe adjustments according to the wearer movements but also provides innovations like:

1. ThinkPod: A wireless link that allows the shoe to link with one's PC.

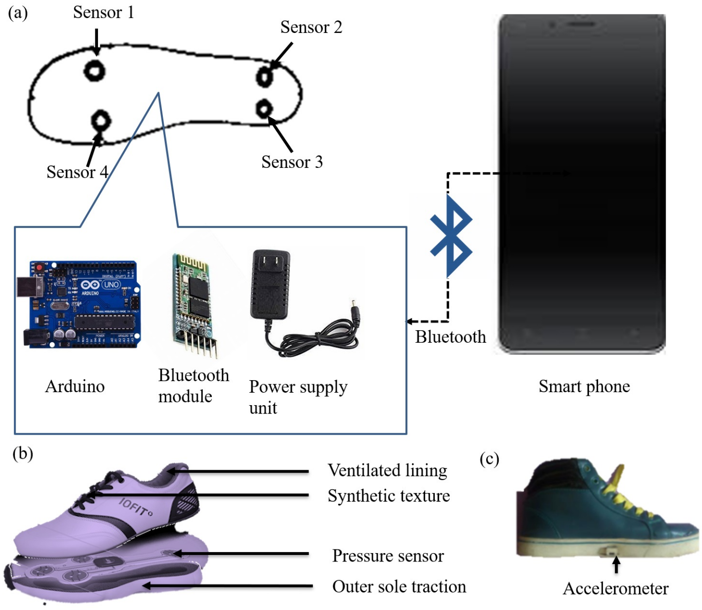

Fig. 4 Smart shoes in medicine and sports. (a) Low power wireless smart shoe system for gait analysis. It uses 4 pressure sensors at its base. The data is read by Arduino and sent over Bluetooth using the HC-05 module. [16] (b) Salted-venture IOFIt golf shoes have an inbuilt pressure sensor. Using mobile app golf trainers can teach to the professional golf player. [17](c) Smart shoes with an accelerometer to measure day-to-day activities.[18]

2. ThinkShare: A new feature for 'Verb for Shoe' users that can exchange business cards and share other information via wireless communication between the shoes of the users.
3. ThinkAdjust: A feature that allows the air bladder in the shoe to be independently adjusted by the wearer.
4. ShoeDoctor: A feature that continuously monitors the shoe's health and alerts when a problem occurs.

Figure 3 (d) shows,The preliminary test of a smart shoe for training foot progression angle during walking for the patients with osteoarthritis has been considered. The smart foot progression angle feedback shoe consists of a sensor module inserted into the heel and the vibration motors sewed into the lateral inner surface of the shoe. An FPA estimation algorithm based on inertial [15] and magnetometer sensing was programmed onto the sensor module to estimate the FPA during early-stance to mid-stance, and the vibration motor provided real-time vibration feedback if the measured FPA exceeded certain thresholds. There was no feedback zone for plus or minus 4.6 degrees; the vibration motor does not vibrate if the foot progression angle for the current step was within this no feedback zone.

Figure 4 (a) shows the low powered wireless smart shoes. The piezoresistance sensors are inserted in the base of the shoe. The smart shoe is comprised of one

Arduino and one class two Bluetooth modules with a battery power supply. This Bluetooth model allows up to 1.5 MBPS sustained, and 3.0 MBPS of user data to be transmitted in each connection with four pressure sensors. Class two Bluetooth module is connected to the transmitter and the receiver pins of the Arduino. This module receives the signal and transfers the data to the smartphone through a Bluetooth communication network. This Bluetooth embedded smart shoe can also be connected to the other Bluetooth devices like tablets, laptops, smartwatches, etc. To process the data, the communication module has two different software tasks. One is for the Arduino and another is for Android. In the Arduino, the program reads an analog signal from the shoe sensors and buffer the signal that is sent to the smartphone through a serial port as a string. Pressure data was collected for the users over some time and every time a subject was tested with different types of walking.

Iofit smart shoes (fig. 4 (b)) has a pressure sensor integrated in the sole. The pressure sensor is used to measure weight. These shoes are also capable of measuring the balance shift in real-time. The wireless data transfer using Bluetooth allows users to connect to the smartphone. It was designed to detect very small changes in the pressure distribution on the overall feet. The sensors are waterproof and placed inside the sole to withstand the excessive weight. It is smart golf shoes that let you analyze golf swing and provide data through a mobile application. Using these golf shoes trainers can accurately analyze the performance of the player and rectify the game from time-to-time.

Figure 4 (c) shows E-Shoes, which is instrumented with tiny wireless accelerometers embedded inside the insole of the shoes. The sensors are smooth and without seams to the users, making the system suitable for recognizing everyday activities. This system has achieved 93% accuracy and average, which is very promising while being energy efficient and easy to use. The sensor used in this study is a wireless accelerometer, i.e., WAX3 developed by researchers at the Open Lab. It is a wireless and small accelerometer with a dimension of 23 x 32.5 x 7.6 millimeters with a weight of 7 grams. The subjects were asked to wear smart shoes and Samsung gear-fit-3 smartwatch. They were asked to perform activities like running, kicking, jumping, cycling, standing, walking in an arbitrary activity. The duration for each activity was varied from 10 to 30 minutes. All the activities were recognized with relatively high accuracy that is over 85% precision and recalls, particularly. The walking activity got the highest precision of 100% and 97% of recall, followed by cycling activity with 95% precision and 100% recall.

4 Electro-mechanical smart shoes

The two vibrating motors insole in the shoe with a sensor module vibrates and gives real-time vibration feedback when the foot progression angle exceeds the threshold value of -40 degrees to 20 degrees. The vibrating angle doesn't vibrate if the current step taken is within the range of no feedback zone. The appropriate progression angle is taken to be 4.6 degrees. The vibration on the lateral side means the person needs to toe-out more and the medial side vibration indicates that the person needs to toe-in more. (fig 3 (d)) Solar panel generator with a piezoelectric generator is used to generate power by using sun rays to charge the smart shoe battery. However, an electromagnetic generator and a piezoelectric generator are a more

	Scan rate	No. of steps	Accuracy	Output voltage	No. of Sensor and actuators
Gupta *et al.* [19]	200 Hz	140	80%	2.45	2
Shu *et al.* [20]	5 Hz	1000000	5%	0.6	6
Eskofer *et al.* [21]	–	–	80%	–	2
Nguyen *et al.* [22]	1.2 Hz	–	100%	–	2
Seo *et al.* [6]	–	1000	20%	5	4
Foxlin *et al.* [23]	300 Hz.	3	20%	–	16
Xia *et al.* [13]	0.5 Hz	20	–	–	1
Jegede *et al.* [11]	–	–	–	0.66-1.21	8
Pham *et al.* [18]	50Hz	1400	93%	–	1
Zerin *et al.* [16]	0.3Hz	–	–	0.01-2.5	4

Table 1 comparison between different existing smart shoes technologies

promising approach for energy harvesting as they can generate high output current level and a very low voltage (typically less than 1V). With this consideration, the electromagnetic generator with a piezoelectric generator is a preferred approach for the generation of power in smart shoes.

5 Mechanical smart shoes

Mechanical actuators consist of magnets that are moved by the spring and pin thrust once the energy is generated in the smart shoes. This technology helps a very little loss of energy while using the device or during the stand by position. The passive pump technology lets you customize the shape of each shoe to fit the precise shape of each foot. As seen in figure 3 (a), the construction of the shoe integrates an inflatable urethane bladder with an air compressor at the side of the shoe and a pressure release valve on the heel. So when you first you lace up the shoe and press the black ball on the side of the shoe. User should inflate the lining, until it molds to the shape of your feet. The air bladder is used to control the amount of air you can pump into specific locations around your foot. Less where the foot relaxes and more to the hard to fit area like hallow between heel and ankle.

6 Comparison of existing smart shoes technologies

The table 6 shows a comparison between different existing smart shoes currently available. The shoe is called smart when at least one actuator or sensor is integrated into it. The actuators could be an electronic or mechanical type. Maximum up to 16 sensors and actuators have been placed on the shoes already. For day-to-day regular activities, 3 or more sensors are required, along with the battery-power and recharging facilities. The output voltage column indicates dc output produced at the output of a piezo crystal mounted at the base of the shoe. This piezo works on the principle of mechanical to electrical conversion. The output voltage is dependent on the number of steps a person takes on an average, in a day. The typical average steps considered is 100 steps/min. The accuracy column in table 6 shows that the smart shoes built can have accuracy as low as 5% and can go as high as 100%. Ideally, the accuracy achieved with a smart shoe sensor should be more than 90%. For medical-grade smart shoes, the accuracy should cross 99.5%.

The no.of steps for which a typical fabricated smart shoe should be tested roughly range is between 3 - 140 steps/mins. The testing steps range can vary from 1000 to 1000000 steps, before launching in the market. The scan rate is a speed at which the sensor senses the data and it can be as low as 0.3 Hz (i.e 1 reading per 3 sec), and it can go as high as 300 Hz (i.e 300 readings per sec). Scan rate depends on the nature of a sensor that is being integrated into a smart shoe. For a sensor like a heart rate sensor, a scanning rate should be high. On the other hand, a pressure sensor can have low scanning rates.

7 Discussions and design guidelines for smart shoes

From the literature review, we found out that most of the shoes were tested on the age group of 25-35 years. Hence, there is a scope that smart shoes can be tested on elderly people who are at more risk of developing diabetic foot or other health issues [21]. There is a lot of scope in designing smart shoes for small kids. [13, 18, 16]. We found that the designed smart shoes were tested on people with height in the range of 1.7 to 2 meters. Hence, the testing was majorly done on taller people, (considering men); no shoes have been designed for females shoes, such as wedges, heels, or sandals. [13, 16]. During testing and development of the smart shoes, the average weight of the person was about 75 kgs, which go as low as 60 kgs and as high as 100 kgs. Hence, we can say that healthy to overweight participants have contributed to the testing, and no shoes were tested with underweight people. [13, 18, 16]. Most of the BlueTooth technology used in the smart shoe was working on the ISM 2.4Ghz band and for continuous data transmission the shoe battery life lasts up to 6 hours. The maximum speed achieved with class 2 BlueTooth module is 3Mbps and Bluetooth LE supports 1Mbps of data rate. Very few smart shoes were integrated with Wi-Fi technology. This is because the personal devices are within range of the user of the smart shoe. Wi-Fi of the range 5.5GHz has been rarely adopted in this technology, as the data transmission rate and the range of the Wi-Fi are very wide. However, while using these smart shoes in hospitals, WAN is used in place of PAN. For such cases, Wi-Fi technology is preferred. [16]. A typical pressure sensor mounted at the sole should work in the range of 0.06 to 15 megapascal, which corresponds to 0.01-2.5 volts at the output of the piezo. The average size of smart shoes RAW data can go up to 135 Mb/day. [16]. The maximum reported sensing range of a smart shoe is around 10 meters. But typically the range of the smart shoe sensor should be within 2 meters. Typically there should be eight sensors at the bottom of the sole to have a proper map of the foot [11]. A smart shoe can generate 5000 data frames in a day [18]. The average output voltage produced by generator type shoes is 2.68V. Typically the diameter of piezo used is 2cm [6]. Generally, shoes should withstand 10 lacs steps per month [20]. Ideal shoe height should be around 15cm max including sole. The length and the width should be less than 35cm, 12cm respectively. The usual humidity range for the diabetic patient is 62The highest speed a designer should consider while designing a smart shoe should be around 40 km/hour (Athletes) [13]. The bent angle, a shoe can withstand should be between 80 - 20 degrees. The typical accuracy of GPS achieved for smart shoes is from 20 - 40 meters. A conventional battery used for smart shoes ranges from 3300 mAh to 4500 mAh. A typical power consumed by smart shoes when all sensors and transmitters are on is 120 mW. A typical shoe height should be around 15 cms max including sole.

8 Conclusions

The smart shoes gather walking patterns from sensor data. It can also, track movements and give suggestions for a healthy lifestyle. Smart shoes are now revolutionizing the future of footwear by designing the product for comfort, convenience, and by monitoring the physical health of the wearer. Technologies such as Bluetooth, accelerometers, sensors, etc. are inserted below the sole of the shoe that can report the activeness of the user via a smart app.

Compliance with Ethical Standards:

Conflicts of interest

Authors N. Mehendale, L. Kamdar, N. Shah declares that he has no conflict of interest also author D. Gokalgandhi declares that she has no conflict of interest aswell.

Involvement of human participant and animals

This article does not contain any studies with animals performed by any of the authors. And also this article does not contain any studies with human participants or animals performed by any of the authors.

Information about informed consent

There were no human participation in current study and hence there was no need for informed consent required in the presented work.

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