# Footwear-Based Wearable Systems


## Abstract

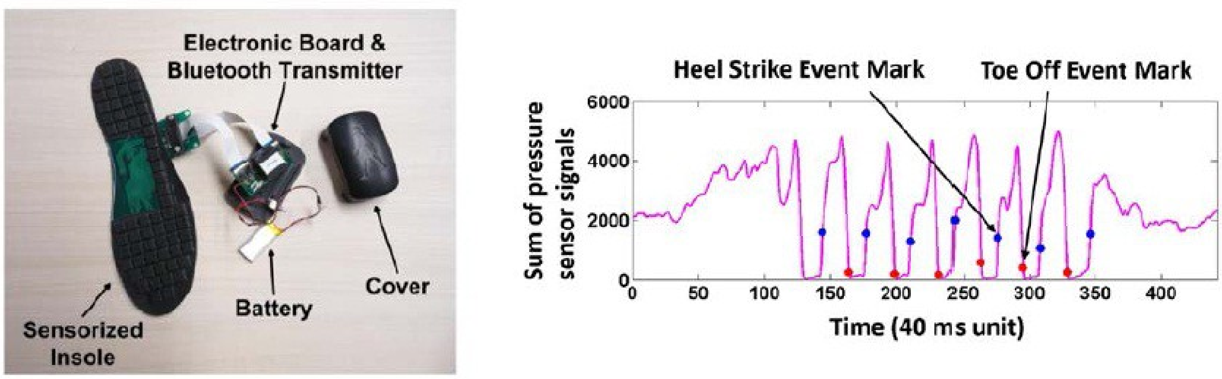
Footwear is an integral part of daily life. Embedding sensors and electronics in footwear for various different applications started more than two decades ago. This review article summarizes the developments in the field of footwear-based wearable sensors and systems. The electronics, sensing technologies, data transmission, and data processing methodologies of such wearable systems are all principally dependent on the target application. Hence, the article describes key application scenarios utilizing footwear-based systems with critical discussion on their merits.The reviewed application scenarios include gait monitoring, plantar pressure measurement, posture and activity classification, body weight and energy expenditure estimation, biofeedback, navigation, and fall risk applications. In addition, energy harvesting from the footwear is also considered for review. The article also attempts to shed light on some of the most recent developments in the field along with the future work required to advance the field.


## Introduction

Footwear is an irreplaceable part of human life across the globe. While the initial necessity was purely to protect the feet [1], they have also become a symbol of style and personality [2]. Footwear acts as the interface between the ground and the wearer's foot. Lots of information can be gleaned from observing this interaction. Attempts to capture this information by integrating sensing elements and electronics in the footwear began in the 1990s, both for academic research purposes and in commercial products [3]. In recent times, development of low power, wireless, unobtrusive and socially acceptable wearable computing systems has become an increasinglyIMPORTANT research topic.This trend is aided by the exponential growth in the electronics industry, which is driving rapid advancements in microfabrication processes, wireless communication, and sensor systems. The applications for footwear-based systems range from simple step counting solutions to more advanced systems intended for use in rehabilitation programs for disabled subjects. Footwear-based systems available on the market or in research laboratories today vary in their sensor modalities and data acquisition methodologies in order to meet different application requirements.Typically, these systems consist of pressure sensors for plantar pressure measurement, inertial sensors (accelerometer and/or gyroscope) for movement detection and a wired or wireless connection for data acquisition. The signal processing of this collected data varies depending on the application, can range from lightweight signal processing methodologies (for example, binary decision trees) running on a handheld device to complex signal processing/machine learning models (for example, Support Vector Machines) running on a PC.Several vital biomechanical parameters can be estimated using sensors placed in the footwear. For example, by placing pressure-sensitive elements in the footwear, foot plantar pressure can be measured. By utilizing pressure-sensitive elements along with inertial sensors, several gait parameters can be calculated. Additionally, by placing actuators in the footwear and measuring gait patterns, one can generate biofeedback to assist patients suffering from stroke. The same set of pressure sensors and inertial sensors can also be used in tracking posture and activity recognition and energy expenditure estimation. These and otherIMPORTANT applications have driven

# Application Scenarios for Footwear-Based Wearable Systems

A person's walk is characterized by their gait, which involves a repetitious sequence of limb motions to move the body forward while simultaneously maintaining stability [4]. Having a normal gait allows someone to remain agile so that they may easily change directions, walk up or down stairs, and avoid obstacles. Patients with neuromuscular disorders are likely to have abnormal gaits and suffer in their ability to perform locomotive activities. Objective measurement and analysis of gait patterns can help in the rehabilitation of such disabled individuals. Figure 1a shows an illustration of an instrumented insole developed for gait monitoring by Crea et al. [5]. There are two kinds of parameters that are computed in gait monitoring applications: temporal and spatial. Some of the examples of the temporal gait parameters are cadence, stance time, step time, single support time, and double support time; while step length and stride length are examples for spatial gait parameters. Gait monitoring is one field of wearable computing where there are a considerably high number of footwear-based systems deployed. Many such systems are compared in Table 1.

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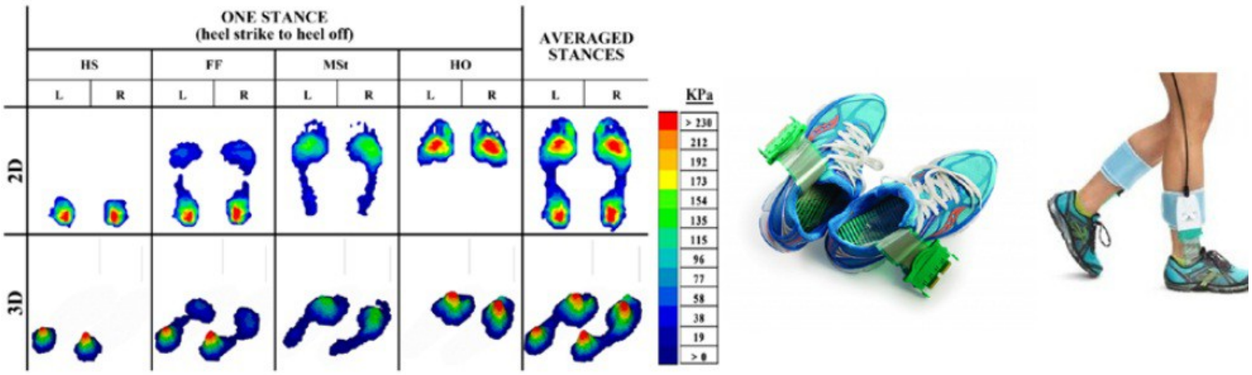
There are force plates available f or gait analysis [6], and there are also systems that make use of the Kinect [7,8]; but footwear-based solutions are much better suited for uncontrolled free living conditions outside the laboratory environment. Footwear is also an ideal location to measure the gait parameters as these applications measure the parameters involved in the movement of foot. By utilizing pressure-sensitive elements, such as force sensitive resistors (FSR), for gait monitoring, temporal parameters such as cadence, step time, stance time and others can be computed.This is done utilizing the heel strike and toe off time events (Figure 1b). The gait monitoring applications extract gait event information from the changes in pressure sensor readings and not the absolute pressure. Hence, the pressure sensing does not need high spatial resolution, so only a few pressure elements are used in such applications. High pressure measurement precision is also not needed, and for that reason, sometimes these are called foot switches.

# Plantar Pressure Measurement

Plantar pressure is the pressure distribution between the foot and the support surface during everyday locomotion activities. Foot plantar pressure measurement applications focus on measuring of a plantar pressure map during one stance phase (heel strike to heel off) of a healthy individual [27]. The foot and ankle provide the support and flexibility for weight bearing and weight shifting activities such as standing and walking. During such functional activities, plantar pressure measurement provides an indication of foot and ankle functions. Plantar pressure measurement has been recognized as an important area in the assessment of patients with diabetes [28]. The information derived from plantar pressure measurement can also assist in identification and treatments of the impairments associated with various musculoskeletal and neurological disorders [29].

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Hence, plantar pressure measurement is important in the area of biomedical research for gait and posture analysis [11,30,31], sport biomechanics [32,33], footwear and shoe insert design [34], and improving balance in the elderly [35], among other applications. For all the above applications, there are solutions that utilize non-wearable systems, such as force plates and force mapping systems [36], but footwear is an ideal location for such measurements. Footwear-based platforms also offer much higher portability and can potentially enable monitoring outside of the laboratory, in uncontrolled, free living applications. Almost all the footwear-based applications reviewed in this work have some form of plantar pressure sensing elements built in to them; however, in this section we place an emphasis on the footwear systems that deal explicitly with plantar pressure measurement.

These systems are compared in Table 2. Figure 2b shows the F-scan® system by Tekscan, Incof a plantar pressure map during one stance phase (heel strike to heel off) of a healthy individual [27]. The foot and ankle provide the support and flexibility for weight bearing and weight shifting activities such as standing and walking. During such functional activities, plantar pressure measurement provides an indication of foot and ankle functions. Plantar pressure measurement has been recognized as an important area in the assessment of patients with diabetes [28]. The information derived from plantar pressure measurement can also assist in identification and treatments of the impairments associated with various musculoskeletal and neurological disorders [29].Hence, plantar pressure measurement is important in the area of biomedical research for gait and posture analysis [11,30,31], sport biomechanics [32,33], footwear and shoe insert design [34], and improving balance in the elderly [35], among other applications. For all the above applications, there are solutions that utilize non-wearable systems, such as force plates and force mapping systems [36], but footwear is an ideal location for such measurements. Footwear-based platforms also offer much higher portability and can potentially enable monitoring outside of the laboratory, in uncontrolled, free living applications. Almost all the footwear-based applications reviewed in this work have some form of plantar pressure sensing elements built in to them; however, in this section we place an emphasis on the footwear systems that deal explicitly with plantar pressure measurement. These systems are compared in Table 2. Figure 2b shows the F-scan® system by Tekscan, Inc

# Posture and Activity Recognition, and Energy Expenditure Estimation

The ever increasing problem of obesity has brought immense importance to study in the field of posture and activity recognition and energy expenditure estimation. Weight gain is caused by a sustained positive energy balance, where daily energy intake is greater than daily energy expenditure. This is typically caused by living a sedentary lifestyle [52,53]. In [14] it was reported that obese individuals spend more time seated and less time ambulating than lean individuals. More than one third of U.S. adults are obese [54] and quantifying posture and activity allocation to help keep track of energy expenditure utilizing wearable sensors is quickly becoming a part of weight management programs.The applications extend beyond weight management programs, as posture and activity monitoring is an important aspect in the rehabilitation programs for post-stroke individuals [55]. Posture and activity classification is a large part of the consumer electronics industry's fitness segment. Fitness applications running on smartphones, smart watches, and fitness trackers are becoming common parts of modern daily life [56–60]. Almost all of these solutions are based on accelerometry and there are many published works on using accelerometer for posture and activity recognition [61–68]. There are also comparisons of commercially available accelerometry based activity and energy expenditure estimation (EE) monitors in [69–71]. In this section however, we focus only on footwear-based solutions used for posture and activity recognition, body weight, and EE estimation.There are several footwear-based systems for posture and activity recognition purposes, and an example of these are the SmartShoe system developed by Sazonov et al. [72] which have been validated extensively for posture and activity monitoring. They have been used with healthy subject groups [30,72,73], people with stroke [55,74] and children with cerebral palsy [75]. The most recent incarnation of the SmartShoe systems, named SmartStep by Hegde et al., has shown the capability to be accurate in posture and activity classification [21,76,77]. Chen et al. have designed a foot-wearable interface for locomotion mode recognition based on contact force distribution [78]. Kawsar et al. have developed a novel activity detection system using plantar pressure sensors and a smartphone [79]. Table 3 contains the comparison of these systems. Figure 3a shows a p

# Conclusions

In this work we reviewed footwear-based wearable systems based on their target application. Existing footwear-based solutions from academic research as well as commercial ones in the areas of gait monitoring, plantar pressure measurement, posture and activity classification, body weight and energy expenditure estimation, biofeedback, fall risk applications, navigation, along with footwear-based energy harvesting solutions were detailed. The article also discussed sensor technology, data acquisition, signal processing techniques of different footwear-based systems along with critical discussion on their merits and demerits. Additionally, we attempted to shine a light on recent trends and future technological pathways for footwear-based solutions.

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