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Wearable Devices for Gait Measurement - A Case for Textile-Based Devices

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ABSTRACT

Wearable devices for gait measurement are devices worn on the body to measure the gait of the wearers. During gait measurement, several parameters are measured and the choice of parameters is influenced by the application and by extension the gait index. Two approaches have been adopted in this research. One is the provision of an overview of wearable devices for gait measurement with a bias towards textile-based "soft" smart wearable systems using information from varied academic sources and databases. The second approach is to map out key scientific research trends within the wearable device classes using the Web of Science database. The focus is to make a case for textile-based gait measurement devices and systems while exploring the key determinants of wearable gait sensor placements and application efficiency. These soft smart wearable systems describe flexible material sensor-based systems which have their sensing mechanisms based on material deformation after being subjected to stress or pressure. This study could therefore serve as an apt reference for the development of soft smart wearable gait measurement systems as it throws light on the various soft wearable gait measurement applications, the bottlenecks in soft wearable device design, opportunities for developing new devices and the merit that soft gait analysis systems possess over their hard gait measurement counterparts.

KEYWORDS

wearable devices, electronic textiles, smart textiles, soft sensors, piezoresistance, gait measurement

INTRODUCTION

A gait describes a pattern of limb movements made during locomotion. One of the few species to have perfected bipedal movement is humans. Their foot's evolvement has been the basis for such a particularized gait. There exist many modes and forms of human gait, ranging from either natural tendencies or due to specialized training. Differences in gait patterns are characterized by variations in limb movement patterns, forces, overall velocity, kinetic and potential energy cycles, and alterations in the contact periods with the ground. Gait measurement is important for many reasons, including medical diagnoses and rehabilitation, sports, computer games and forensic applications.

Gait measurement parameters are numerous and may depend on the area of application. Examples include step length, velocity, cadence, motion intensity, step symmetry, step variability, step regularity etc [1]. About 21 of these gait parameters have been identified by Muro-de-la-Herran et al. [2]. The choice of gait parameters is based on the particular gait application and by extension the type of index. Several clinical gait indices that exist in the literature include the Gait Deviation Index (GDI), the Gait Variability Index (GVI) [3], the Gillette Gait Index (GGI) [4], and the Gait Kinetic Index (GKI). Also, a non-clinical index discovered in the literature is the Multi-feature Gait Score (MGS) applied by Ben-Mansour et al., in their gait analysis study [5].

Medically it has been established that alterations in gait expose salient information about a person’s quality of life. Credible data support the belief that reliable knowledge on the evolvement of a diverse range of nervous system disorders such as Parkinson's or multiple sclerosis; systemic disorders such as cardiopathies; changes in deambulation dynamic; ageing-induced diseases, which affect a vast majority of the general population can be extracted from gait parameters [2]. Monitoring and evaluating precise and reliable data of gait characteristics at a specific time, and even more importantly, over time, allows for early diagnosis of diseases as well as any complications thereby helping in finding the best treatment.

In sports biomechanics, gait analysis is used to improve the performance of an athlete and injury prevention [6]. Since the prevention and management of injuries are of high importance in any sport, a comprehensive evaluation of gait serves as a dependable indicator of the likelihood of an athlete developing a condition, both on and off the field. For example, a static and dynamic evaluation of an athlete is important in spotting any biomechanical anomalies such as hyperpronation, plantar misalignment or Achilles tendinitis during gait.

In forensics, gait analysis plays an important role in solving many crimes. Forensic gait analysis describes the assessment and analysis of the suspect's gait features and patterns and matches these features with crime scene evidence for criminal/personal identification [7].

Previous studies have classified gait systems into several different categories. A study by Muro-de-la-Herran et al. classified gait measurement systems into wearable and non-wearable systems [2]. Others include independent systems (Motion capture cameras), partially independent systems (Gait mat/pressure mat, Acoustic tracking system) non-independent systems and Hybrid technology [8]. We also however contend that gait measurement systems can generally be classified into four classes’ namely visual observation (Observational gait analysis), video gait analysis systems, surface mountable gait analysis systems and wearable gait measurement systems. Observational gait analysis is a qualitative approach to gait analysis used by clinicians to assess gait deviations without the use of instruments or technological gadgets [9]. Video gait analysis involves the use of video recording for the analysis [10]. Surface mountable (force plate/pressure plate) systems make use of floor sensors [11]. Wearable devices for gait measurement are devices worn on the body to measure the gait of the wearers. Wearable systems tend to provide a more affordable and convenient solution for gait monitoring, showing great potential for long-term and real-time gait evaluation; as such this study focuses on wearable gait measurement systems. We are thus extending the classification of wearable systems further by classifying wearable systems into soft and hard wearable systems. This study seeks to make a case for soft wearable devices in apparel and shoes, ubiquitous articles used by all, thereby expanding the access and application of gait monitoring systems. In this way, daily tracking and gait analysis will be possible and comprehensive data can be extracted for examining user posture control mechanisms during body movement and providing enhanced clinical pieces of evidence for diagnoses and treatments [12].

These wearable systems tend to be characterized by more flexibility and mobility, with enhanced performance and efficiency relative to circuit design solutions, power consumption, and communication technology, with a decreased cost in comparison to surface embedded systems [13]. Wearable systems also allow for gait analysis in real-time which is pivotal to the development of gait rehabilitation methods and assistive devices for applications outside both the lab and hospital environments [14]. The study also seeks to serve as a precursor study and an apt reference for the development of soft wearable gait measurement systems.

KEY DETERMINANTS OF WEARABLE GAIT SENSOR PLACEMENTS

A standard gait pattern relies on an array of biomechanical features, controlled by the nervous system for enhanced energy conservation and balance [15]. For example, the biomechanics of squatting includes consideration of the position and/or movement of the feet, hips, knees, back, shoulders, and arms. These biomechanical features of the body during normal gait have been termed key determinants of gait. Six basic determinants of gait have been discussed in literature including rotation and tilting of the pelvis, flexion of the knee, ankle and foot motion, movement of the knee and pelvis' lateral displacement [16]. The most important joints of the lower extremity are the hip, knee, ankle, and foot and their biomechanics inform the placement of the sensor.

The gait cycle is established to consist of 60% stance phase and 40% swing phase which alternate for each lower limb [17]. The stance phase describes the entire time that the foot under consideration is on the ground whilst the swing phase marks the period when the foot under study is not touching the floor. Thus normal gait requirements have been found to encompass stance stability; swing phase toe clearance; swing phase pre-positioning; adequate step length; and ample mechanical and metabolic efficiency.

Appropriate placement of gait measurement sensors often ensures a simplification or even elimination of any tedious calibration required for gait measurement algorithms [14,18]. The choice of sensor placement may also depend on other factors such as accuracy, convenience and level of acceptance by users. The placement of gait measurement sensors can also be based on several variables related to variations in muscle activity patterns during walking and may include Spatial-temporal variables, Kinematic variables, and Kinetic variables [12].

Wearable sensors placed based on spatial-temporal variables are predominantly on the lower limbs of the user. Spatial-temporal variables afford gait analysis from the perspective of distance and time within the cycle. The spatial variables otherwise known as the distance parameters include the step length and stride length, step width and foot angle [19]. The temporal variables also known as the time variables include the cadence, speed or velocity and the time of single limb support time. Spatial and temporal gait parameters are clinically acknowledged and their relevance in the motor pathologies assessment is not in doubt, since they normally occur in established combinations which can be altered by pathologies [20].

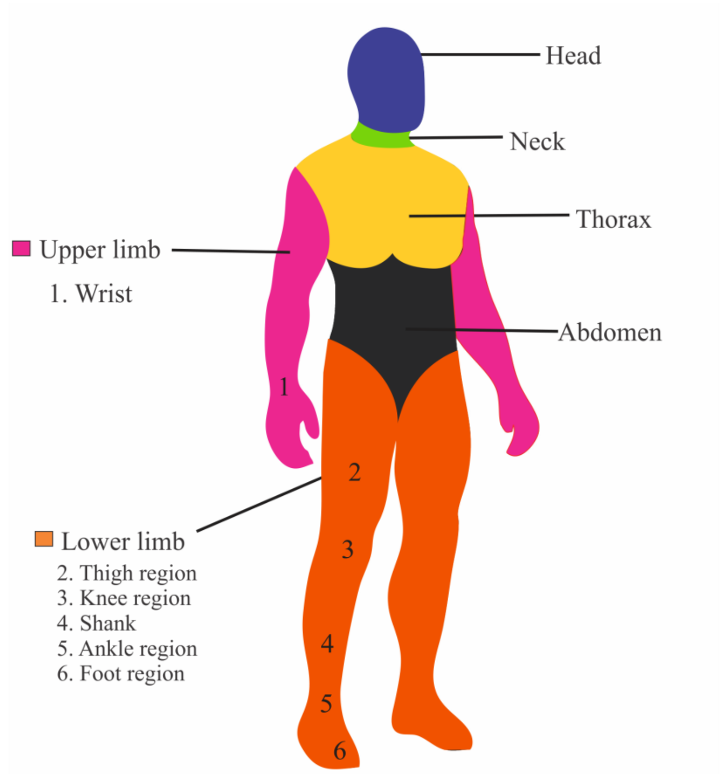

Figure 1. Possible areas of attachment based on these three variables

Kinematic variables of gait describe the extent, speed, and direction of joint movement or body segments. Kinematic variables are applied in gait analysis to define body segments' position and orientation, joint angles, the accompanying linear and angular velocities and acceleration.

Kinetic variables otherwise referred to as movement measures consist of forces and moments of force that ensue during movement. These are forces and moments between a body and its surroundings and internal forces and moment's consideration. These variables comprise the hip flexion moment, the range of ankle moment, the range of knee moment, and the ratio of double support. Cumulatively these kinetic variables represent 94% of the fluctuation in gait speed [21]. Thus both Kinematic and kinetic variables which are biomechanical parameters can essentially be applied in determining sensor placement on the various parts of the body shown in Figure 1. Research results have however established optimum gait measurement results can be ascribed to certain specific areas of the body.

A recent study by Hutabarat et al. reported that about 78% of wearable gait sensor researchers recommended sensor placement on the lower limb with the foot claiming the chunk at 41% and 18% of attachment to the trunk [22]. Also, 25% of sensor placements were attachments featuring combinations of foot, trunk and head [22]. Out of this 25%, 22% were between the lower limb and the corresponding trunk and head regions. Other studies also corroborate the overwhelming general preference for the lower limb (shank and foot) as being the region of choice for the placement of wearable gait measurement sensors [14].

Another area such as the wrist has become popular for gait sensor placement of late due to the emergence of smart watches and wristbands. However, as opposed to the trunk and legs, the relationship between wrist movements and gait is not straightforward. The hand may be motionless when carrying items or when placed in the pocket during walking. These instances of hand disengagements may potentially pose a serious challenge to accurate wrist-based gait measurements [23].

The use of smartphones for gait sensing also allows for phones to be placed in the pocket of the user. Depending on the position of the pocket the sensor may be aligned to the waist, the lower back [24-25], the inner thigh [26], the abdomen, or the thorax regions. It has been observed that most smartphone gait analysis methods prefer the lower back body part of the user because it delivers a comparatively less noisy signal, however, in the normal usage of phones that is not the preferred body part. This therefore in a way defeats the idea of an unobtrusive mode of smart wearable device usage. Earlier studies have corroborated the idea of using head-worn devices in gait analysis [27]. Tong-Hun Hwang et al. also reported that head acceleration helps analyze gait events and gait patterns, however even though these studies confirm the feasibility of the head and neck in gait sensing, applications are still limited compared to other body parts [28].

WEARABLE GAIT MEASUREMENT SYSTEMS AND DEVICES

A wearable technology device describes a miniature, handy, personal, minicomputer that deploys different types of sensors to detect, calculate and record peculiar physiological or mechanical features of the human body. Several technologies have been applied for the development of wearable gait sensing systems including strain and pressure sensing systems, magnetometers, accelerometers and camera systems [2,29].

This study thus is focused on wearable gait measurement systems and devices and classified these wearable systems into soft wearable and hard wearable systems as shown in Figure 2. Soft wearable systems describe systems or devices that have their sensing mechanisms based on flexible material sensing mechanisms. Textile sensors based on optics, piezoresistance, resistive sensing, piezoelectricity, impedance, capacitance, inductance, and so on can be regarded as soft sensors. Soft systems or devices tend to be inherently embedded into garments or shoes and their sensing mechanisms are based on material deformation and or vibration whilst hard systems refer to predominantly electronic devices or non-fabric fashion accessories.

The most widely applied wearable gait measurement devices and systems are so-called hard wearable systems. Their popularity is due to obvious reasons such as low cost, the comparative maturity and availability of such technologies. Ubiquitous devices like smartwatches, smart spectacles and smart wristbands for example are seen as a transition from their regular counterparts that do not offer many features that the modern smart ones provide.

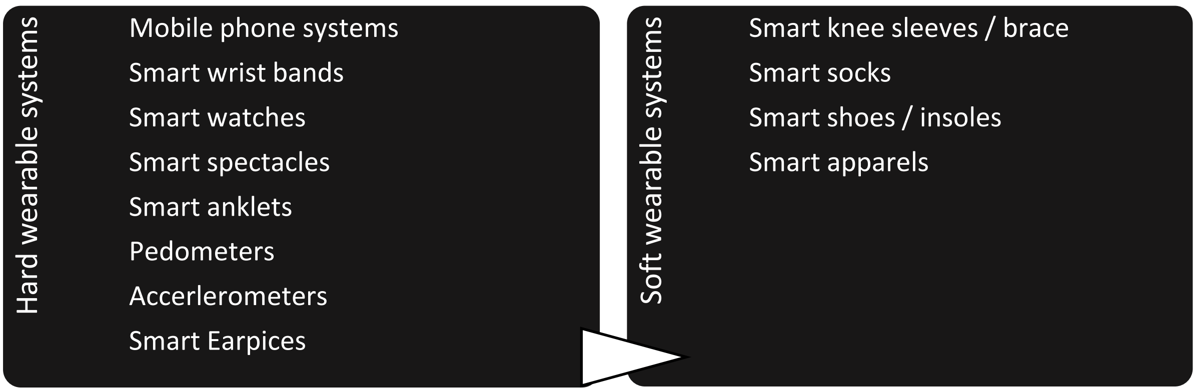

Figure 2. Gait sensing systems classified into hard wearable and soft wearable systems

Subsequent discussions take a look at the various hard wearable gait sensing systems. Based on this classification, the authors infused an analysis to map out the key scientific research trends within the wearable device classes. Using the Web of Science database, searches were conducted under the above classifications inputting all the hard and soft wearables in Figure 2 as the keywords. A total of 312 papers were used for hard wearables and 359 papers for soft wearables. Shoe-related papers formed the majority consisting of 196 papers followed by mobile phones 150, accelerometers 110 and socks 98 in that order. Articles were not restricted to a period; manual screening was done to remove articles not related to the subject matter. Bibliometric maps were visualized using VOSviewer Version 1.6.16 [30].

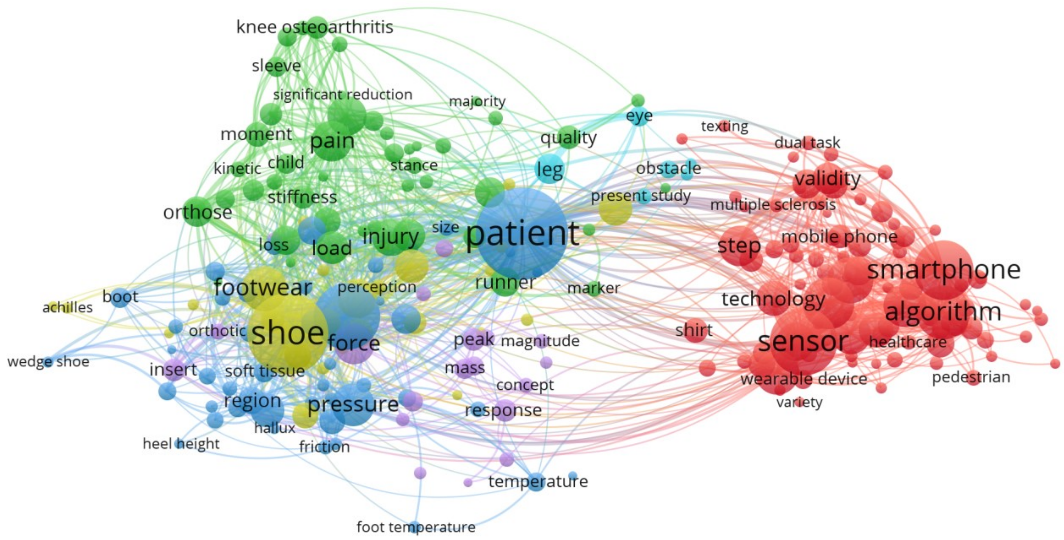

Figure 3. Visualized networks of keywords appearing in titles and abstracts of studies under the hard and soft wearable system

The bibliometric maps show the words that featured most in paper titles, abstracts, and keywords. The words in bigger nodes featured more in the literature than those in smaller nodes. The results enable researchers to identify the main themes in the research domain. Figure 3 shows the network visualization of keywords that appeared most in the titles, abstracts, and keywords of the articles. Each node corresponds to the frequency of a keyword; hence bigger nodes indicate higher frequencies. Keywords that appear closer to each other and in the same cluster are strongly linked. The keyword co-occurrence has 241 nodes (keywords), 5 clusters, and 10,512 links. The five keyword clusters consist of (1) shoe, indicating shoe-based devices and soft sensors (yellow colour); (2) Patient, featuring as the central node, and biggest of all nodes is an indication that both soft and hard wearables are predominantly health-related (blue colour); (3) Sandwiched between the blue and yellow nodes are the purple nodes which explain some device test methods and terminology. (4) The green cluster relates to the health conditions or discussions about the patients (users) (green colour). (5) Sensor, algorithm, smart phone all within the red cluster represent studies done on the hard wearable devices (red colour). The results of this analysis suggest that even though hard wearable devices are dominant in terms of the number of devices, soft wearables tend to present a strong mix in terms of healthcare utility applications.

Mobile phone systems

Most smartphones have inbuilt inertial measurement units (IMUs) made up of accelerometers gyroscopes and optionally magnetometers. These accelerometers and gyroscopes within the IMU generate electrical signals in proportion to the acceleration and angular velocity. These signals undergo quantification concerning the three axes, X, Y and Z, and relative to the frame on which the inertial measurement unit chip is fixed. Those that also include magnetometers mostly assist in calibrating against orientation drift or magnetic fields surrounding the device. For gait analysis, these data are converted into commonly used gait parameters such as velocity, step length, and cadence [31]. Smartphone gait measurement systems are thus based on these inertial units.

A study utilized this inbuilt smartphone inertial system to calculate gait by developing a gait parameter collection and visualization system via a smartphone-to-laptop connection. The proposed system collects accelerometer data from a smartphone and calculates the gait parameters related to walking activity on a laptop interface [32]. Other smartphone-based gait systems are directly based on Apps that are installed on smartphones and make use of the inbuilt inertial sensors to measure gait [1,33]. Several other proprietary examples such as SportGait, Gait Tracker etc. exist on the market. It has however been suggested that these cost-effective sensors installed in smartphones tend to be plagued with low measurement accuracy and inferior measurement stability, thus resulting in measurement errors [34].

Smart spectacles

The so-called smart glasses or smart spectacles describe a type of head-don display technology that functions as a computer and aids users to access information within their visual field of view in real-time [35]. According to Hellec et al., most elderly people wear glasses during daily living activities, embedding an IMU in such a wearable device of daily utility could portend a technological innovation for gait analysis [36]. They thus embedded an IMU (accelerometer) in an eyeglass on the right temple. They then proceeded to test twenty young volunteers to ascertain the validity and reproducibility of step duration and step length parameters estimated during walking. Other applications that exist in the literature include gait analysis of 20 healthy young adults walking on a treadmill at their preferred walking rates in four 5-minute walking trials [36]. Figure 4(a) presents Epson's BT200 smart glasses that have found application in detecting Freezing of gait (FOG) in Parkinson's disease patients experiencing FOG [37].

(a) (b) (c)

Figure 4 (a) Epson's BT200 smart glasses [37]; (b) RehaGait smart anklet system [38]; (c) Sensoria Fitness Smart Sock [39]

Smart anklets

Anklets are items (such as an ornament) worn around the ankle. Anklets or ankle-based trackers are based on IMU-based systems similar to those discussed in the smartphone systems. This study reports a gait analysis system based on an embedded IMU and feedback system RehaGait (HASOMED GmbH, Magdeburg, Germany)[38]. It incorporates a pair of IMUs anchored to the user's footwear by straps allowing for a lateral placement of the sensors just beneath the ankle joint (Figure 4b).

Wearable Accelerometer

A sensing device with the capability of computing the linear acceleration of a user is referred to as an accelerometer. Figure 5(a) shows a sample wrist-worn accelerometer from Sportsens [40]. Accelerometer metrics include local acceleration due to gravity, also referred to as specific forces. Portable accelerometers just like the other related wearable systems when equated to lab-based gait analysis methods have advantages such as low price; handiness, and uncomplicated reading interfaces for non-technical users. However, these devices still appear to exhibit poor accuracy and precision, with a heightened vulnerability to noise and external factors. Most accelerometers are also inherently not wearable so placement on the body has to be improvised through means such as taping etc. [41]. However, they continue to serve as inexpensive alternatives to expensive, complex and large laboratory systems.

A gait measurement system based on accelerometers was developed by Correa and Balbinot [42]. It consists of a wireless system showing a virtual model of the human body and has a sampling rate of 50 Hz. The Accelerometers were attached to the thigh and leg to effect measurement of the joint angles between the hip and knee during walking tests. A small and wireless accelerometer system developed using two 3-axis accelerometers was applied for the measurement of temporal gait parameters by Lee et al. The researchers contend that the system offered a reliable means for the identification of temporal gait parameters [43].

(a) (b) (c) (d)

Figure 5. Some Hard wearable systems and devices for gait measurements - (a) Accelerometer [40], (b) Wristband [44], (c) Smart wristwatch [45], (d) Wearable pedometer [46]

Smart Wristband

Smart wristbands (i.e. smart bands or fitness bands, smart bracelets), generally referred to as fitness trackers normally worn on the wrist are devices more devoted to personal activity tracking. Typically a fitness tracker tends to be cheaper than a smart watch because of low-priced hardware and often limited number of sensors. As a result, wristbands generally also tend to have satisfactory battery life and a simplified interface for presenting tracking results. An example of a wristband (Xiaomi 6) is shown in Figure 5(b) [44].

In a study presented by Rincón et al., a set of two wristbands embedded with portable accelerometers was developed for their experiment on arm swing changes due to the incidence of Parkinson's disease (PD) [47]. Each band has two accelerometers (ADXL335, three-axis sensors with a resolution of ±3 × g) connected on two Arduino Simblee Bluetooth low energy programmable cards. A lithium battery with a capacity of 400 mAh - up to 12 hours of battery life is connected to each one of them. Another application of smart wristbands in gait sensing is the use of Microsoft Band 2 on a total of 60 users for gait biometric authentication [48].

Smart wrist watches

For practical gait analysis, global navigation satellite systems (GNSS) or inertial sensors possibly integrated with a smart wristwatch exist [49]. A smartwatch is a device worn on the wrist that mostly serves as an accessory to a smartphone and can display notifications and track personal activity and associated metrics. All modern smartwatches are embedded with accelerometers and most of them can be utilized to compute a type of movement, count steps, compute energy expenditure and energy intensity, as well as an estimation of sleep patterns etc. [50]. Figure 5(c) shows an example of a smartwatch [45].

However, validating smart watch-derived measurements for scientific or clinical applications is complex as the majority of computed metrics recorded from end-user wearable devices e.g., built-in energy expenditure and step counts are deduced from covert, proprietary algorithms with obscure modelling concepts that have not been subjected to medical certification procedures [51]. Nonetheless, smartwatches continue to enjoy usage in gait applications within the sphere of gait analysis research and outside the hospital environment due to suggestions by numerous research results about their relative accuracy [52]. This suggests that wrist sensors can be a feasible alternative to lab-based systems and clinical gold standards due to their ubiquity and comparatively low price. Three main parameters of gait including step length, swing time and stance time were analysed by a study conducted by Erdem et al. using smart watch gait recognition [53].

Wearable Pedometers

Pedometers describe low-priced motion sensors which are responsive to oscillations in the acceleration of the body segment such as the hip, thigh, wrist, etc. within gait cycles. The outputs they provide are by way of step counts within the specified time frame. Figure 5(d) shows a Yamax - CW600 Digi-Walker Pedometer [46]. Different pedometer types may feature a few different setup steps, but the general procedure should be similar for most devices.

The disparity in cost and accuracy among pedometer types stems from the differences in internal configurations in their applications. There are at least four different pedometer sensing mechanisms and they include a spring-suspended lever arm with metal-on-metal contact, magnetic reed proximity switch and horizontal beam, piezo-electric crystal or MEMS, i.e. an accelerometer-based system and Global positioning system (GPS) receiver [53]. Pedometers have typically exhibited inaccurate readings during slower walking speeds. Some studies suggest error rates as high as 96% [53]. However, their application in gait analysis continues to evolve with several studies aimed at finding ways to improve accuracy. A study by Crouter et al., evaluated the impacts of walking speed on the precision and reliability of ten pedometer types [54]. Several instances were reported including pedometers underestimating steps at 54 m x min-1, but improved accuracy for step counting at faster speeds.

Smart earpieces

Given the overly increasing spate and sustained proliferation of ear-worn devices, the emerging frontier of wearable gadgets seems to be for ear-wearables. Thus a study investigated the feasibility of an earpiece-based gait identification system. A study by Ferlini et al., presented an ear-piece-based system that takes advantage of an in-ear facing microphone which makes use of the wearable's occlusion effect to precisely detect the user's gait from within the ear canal, without undermining the general utility of the earphones [55]. They reported that with data adduced from 31 volunteers, the system attained a Balanced Accuracy (BAC) of up to 97.26% with a very low False Acceptance Rate (FAR) of 3.23% and False Rejection Rate (FRR) of 2.25% respectively.

A CASE FOR SOFT WEARABLE SYSTEMS

Even though the popularity of hard wearable systems and devices for gait measurement is unmatched, having wearable devices made with soft sensors inherently embedded into garments or shoes carries many advantages. Soft wearable systems which are flexible tend to fit intimately to the human body, are lightweight, and deliver wearer comfort when used for extended periods [56-57]. Therefore the application of soft wearable devices as an alternative to embedded systems and video surveillance gait analysis methods will not only be comparatively inexpensive but also permit studies outside the laboratory environment.

Several fabrication routes and design concepts for the development and fabrication of soft smart wearable devices have been researched and continue to attract new technologies. In our previous study, we dealt extensively with soft strain or deformation sensors based on different transduction mechanisms such as piezoresistance, piezoelectricity, etc. [58]. Deformation or strain-related sensing is by far the most applied sensing mechanism for designing soft wearable devices. Weaving, knitting as well and other non-woven techniques have proven successful in fabricating these soft-sensing devices.

However apart from strain and deformation-related sensors, proximity sensing mechanisms have also been applied in wearable devices but have not yet found wide application for gait sensing [59]. Proximity sensors are devices that identify the presence or movement of objects without requiring any physical touch. They convert this captured information into an electrical signal. Proximity sensors possess contactless sensing capabilities, which means they can operate without being influenced by surface conditions. They also have a longer lifespan and can provide quick responses [60]. Some applications already exist in the literature [61]. Proximity sensing mechanisms tend to possess the advantage of eliminating wirings and physical wire connections as pertain to the current sensing arrangements [62].

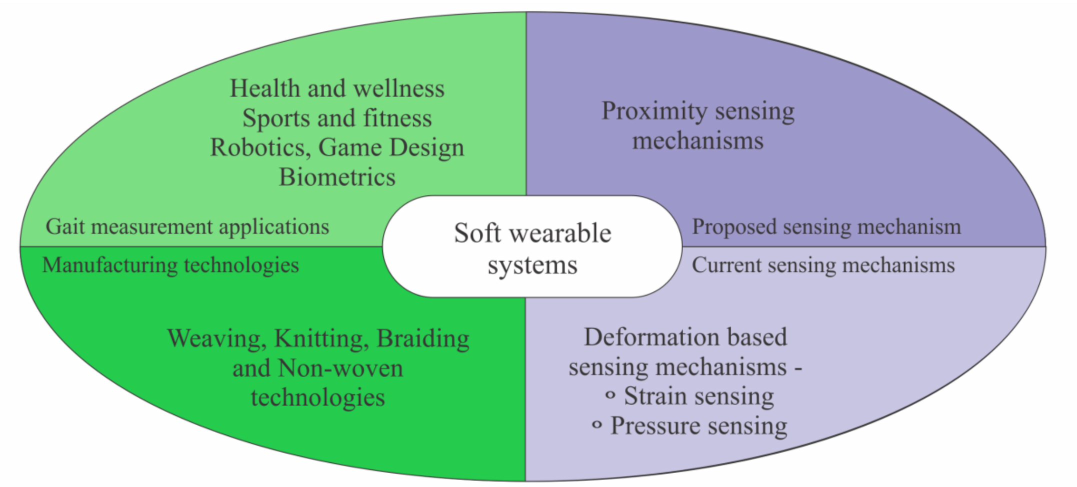

Figure 6. Overview of Soft Wearable Systems

Figure 6 presents a schematic overview of soft wearable systems. The proposed overview identified the main sensing mechanisms, proposed sensing mechanism, areas of application as well and suitable textile manufacturing technologies.

Furthermore, keyword co-occurrence analysis of research work done on soft wearable systems was visualized using VOSviewer.

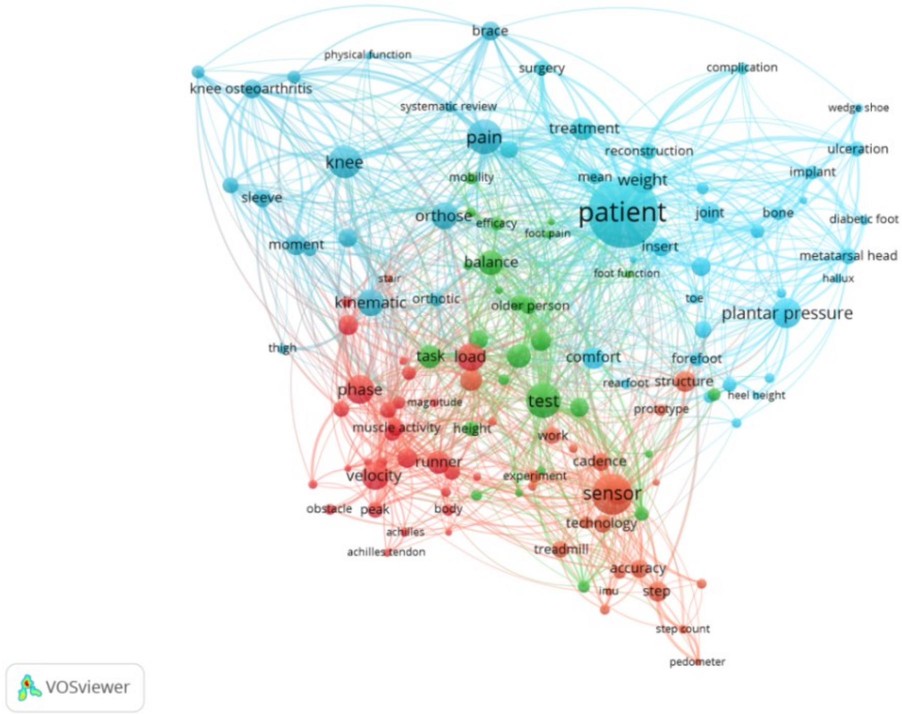

Figure 7. Visualized networks of keywords appearing in titles and abstracts of studies under the soft wearable system

The keywords used were the list of soft wearable devices in Figure 2 as well as soft wearable systems, soft wearable devices, electronic textiles and wearable textile sensors. The results reveal that the majority of applications are health-related and therefore, as can be seen, the blue cluster features parts of the body and even some health conditions that soft wearable devices are applied to. This is shown in the network visualization of keywords that appeared most in the titles, abstracts, and keywords of 359 articles on soft wearables analyzed in VOSviewer shown in Figure 7. The red and green nodes cluster features sensing technology and device test parameters.

Smart knee sleeves/braces

Knee sleeves describe a stretchy band of fabric worn over the knee. The wearing of knee sleeves is one possible means for both boosting the kneecap during activity and reducing pain [63]. Knee sleeves provide only minor support, compared with knee braces, which offer a wider range of support. Knee sleeves, while technically not a brace, tend to be the most prevalent type of knee support donned by the more casual physically active user and average athlete. This study uncovered that the majority of knee sleeve applications in gait research were not necessarily smart knee sleeves but were studies based on the impact of ordinary knee sleeves on gait as referenced in the following studies [64-68]. This therefore suggests that knee sleeves when rendered smart by embedding sensors could provide improved utility in general gait research. Also, smart knee sleeve applications that fit our definition of soft sensing systems were rather limited. The common cases available are the embedment of hard systems or devices into knee sleeves and braces. Typical examples existing in the literature involve the adoption of soft sensor fusion (combined e-textiles and tri-axial accelerometers) for ambulatory human motion analysis [69]. The integration of a potentiometer into a knee brace [70], and direct embedment of IMUs [71]. The drawbacks of these systems are that, they tend to be bulky, not durable and are devoid of wear comfort. However, this review discovered a few examples of smart knee sleeve applications featuring actual soft sensors in the following references [72-73].

Smart socks

According to a patent published by Martin et al., a smart sock describes a system, comprising one or more materials fitted to at least a foot of a user; one or more integrated sensors for measuring information associated with a user located within the one or more materials; and a transceiver wirelessly communicating the information [74].

Generally, smart socks have been used to measure plantar pressure directed at diagnosing diabetic foot conditions however, some gait-specific smart sock applications have also existed in literature [75-79]. A study by Lu et al. presented a sock sensor system designed to compute the counting of steps during gait [80]. The system utilized pressure sensors installed inherently within the sock material. This device then subsequently relays the recorded data wirelessly via Bluetooth to a customized smartphone application. These researchers contend that smart socks exhibited a high level of precision (i.e., < 5% error in comparison to the actual step count) during self-determined walking and running tests in both healthy young and older individuals. One of the most popular smart socks is the Sensoria fitness smart sock shown in Figure 4(b). Sensoria smart socks are infused with textile pressure sensors and are credited to have the capability of analysing gait parameters in real time.

Smart insoles / Smart shoes

The shoe is an important ubiquitous wearable article, lightweight, unobtrusive, and indispensable when undertaking open-air exercises. Experts believe that shoes were invented roughly 40,000 years ago, based on archaeological and paleontological evidence [81]. Studies about Smart shoe-based gait systems are predominantly insole systems [82-84]. Originally, the foot insole design has been applied in numerous health management situations such as foot ulcers and so on [85]. Insole gait measurement systems therefore become additional functionality over existing applications. Insole systems can estimate the distribution of the plantar pressure within a shoe [86] and also possess the capability of rendering a high number of recorded steps, thereby ensuring a long-term recording of gait, both indoors and outdoors [13]. Insole gait measurement systems are available in wide variants based on optoelectronic sensors, accelerometry and gyroscopes force-sensing resistors (FSRs), capacitive sensors, and piezoelectric sensors [87].

Smart Insoles gait measurement system dubbed Cyber-Physical System (CPS) fashioned and applied for restriction-free environment gait parameters measurement of multiple users was presented by [88]. This CPS consists of installed master software on a computer and several multi-sensor health device units in the form of smart insoles. Each of these insoles is made up of 12 Force-Sensitive Resistor (FSR) sensors, an Inertial Measurement Unit (IMU), a Wi-Fi-enabled microcontroller and a power source for powering all components however; their precision tends to be inferior to that of platforms. Even though we placed smart insoles under soft systems, there are related insole systems that also essentially feature commercially available microsensors, computing, and wireless technologies and this category of sensors does not qualify as soft sensors [88]. Those that suit our classification are soft sensors such as parallel capacitance-based pressure sensors, using conductive textiles etc. [90].

Smart apparels

Studies generally demonstrating the application of wearable technology for estimating gait parameters are common knowledge but the achievability of gait monitoring schemes using smart garments is rather rare. A smart shirt developed by Politecnico di Milano, SensibiLab, Lecco, Italy has been demonstrated to be applied for gait analysis. The system incorporates two textrodes installed into the cloth and a three-axial accelerometer, linked by two nickel-free material fasteners. The t-shirt is linked to a customized App for gathering and processing gait data in the form of tri-axial-acceleration (anterior-posterior, mediolateral and vertical) and also providing a concurrent recording of the user's ECG data [91]. A study by Mokhlespour et al. was applied to assess the accuracy of a smart shirt system for differentiating between normal gait and four distinct simulated gait abnormalities [92]. The system however comprised of commercial instrumented socks and a custom instrument shirt. Other applications include posture shirts for dynamic balance in Parkinson's sufferers [93]. AI-equipped photonic smart garment for movement analysis [94] and the application of highly elastic knitted sweatpants for gait monitoring [95].

OUTSTANDING ISSUES ABOUT RESEARCH AND COMMERCIAL DEVELOPMENT OF TEXTILE-BASED (SOFT) WEARABLE DEVICES

Wearable devices are generally and by extension, soft wearable devices are bedevilled with several issues. They include but are not limited to negative user experience stemming from short battery lifespan [96], data inaccuracy and unreliability, lack of software reusability, manipulation of users' data, lack of encryption and some other technical issues [97].

The difficulty in fabricating soft wearable devices is one of the thorny issues that continue to persist. The need for the development of new sensitive yarns based on feasible technologies (conductivity, optics), with good flexibility, and at suitable yarn counts is still on the horizon.

Wearable soft sensor signal extraction and processing is one area that needs further development. Signal processing systems to connect and extract sensor information need to be lightweight and also possess good form factor [58].

Low battery life is a concern for many soft wearable devices. Battery size and space are limited resulting in low capacities which ultimately affect data collection. Frequent charging or replacing batteries can inevitably reduce the practicability of devices and the preference and satisfaction of users [98]. Proposed remedies to this problem have been the application of energy harvested from the body [99], and wireless power delivery among others [100].

One of the major issues with soft wearable technologies is data inaccuracy, unreliability, and or invalidity. As wearable technologies are being increasingly used for clinical research and healthcare, it is critical for data obtained from soft wearable technologies to be accurate, valid, reliable, and reproducible when compared with data collected by gold standards as measurement errors may affect research conclusions and impact healthcare decision-making [101-102].

Currently, electronic parts of signal processing systems usually required for these systems tend to possess some rigidity, poor washability, high prices, and devoid of satisfactory attractiveness in some cases [58]. The implication of soft wearable system research is to reduce or eliminate these drawbacks.

CONCLUSION

The study presented the extensive application of wearable devices for human motion tracking and analysis. The contention therefore is that the use of data adduced from these smart wearable devices and systems may afford physicians and other health practitioners insights into the lived experiences of their patients and enrich their assessments and plans of care. Also, activity tracking can be encouraged and enhanced by the usage of these devices.

The ubiquity, low cost, and obtrusiveness among other reasons of wearable devices make their use for both research and in non-hospital environments indispensable. This stance is further supported by the evolution of IOT technology.

The authors contend that the overwhelming majority of the devices and systems that exist in literature are what this study classified as hard wearable systems. This is an indication that opportunities still exist for the development of soft wearable systems.

The study uncovered that soft systems are predominantly suited for health care applications, especially knee brace and sleeve which have traditional knee pain reducing and knee support applications and socks which hitherto have had health care applications. The integration of wearable technology into these articles will not only satisfy the needs of the user during everyday activities, where mobility monitoring is desired but also expand the functionality of existing articles.

Even though the study sought to illuminate the importance and encourage research in the development and application of wearable soft sensing systems for gait analysis, it is instructive to note that these systems cannot independently function without the attachment of signal acquisition and processing devices. Miniaturization of signal acquisition and processing units /devices and the use of flexible and pliable materials for the design and fabrication of these devices is key to ensuring wearer comfort in wearable soft sensing systems for gait analysis.

Author Contributions

Conceptualization – Raji RK and Wang W; methodology – Li N; resources – Han J; writing-original draft preparation – Raji RK; writing-review and editing – Li N; visualization – Wang W; supervision – Han J. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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