

Wearable sensors used for human gait analysis

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Abstract

This paper briefly presents recent developments in the field of wearable sensors and systems that are relevant to the area of normal and pathological human gait analysis. By using wearable sensors, it is possible to monitor the pathological gait disorders and alterations and the changes in balance in the people and prevent or diagnose of different diseases. The most usable wearable sensors and their applications in clinical field are presented based on specialty literature.

Keywords: wearable sensors, clinical gait analysis, electrogoniometers, inertial sensors, electromyography sensors.

Introduction

Nowadays, the importance of measuring and analyzing gait variability has increased and it is more and more recognized and used in biomechanics and in clinical research field. Clinical gait analysis usually consists of measurement of gait parameters, kinematic analysis, kinetic measurement and electromyography. Spatial and temporal parameters of gait provide useful diagnostic and therapeutic information, if they are accurately measured [1]. In the medical field, the knowledge of gait characteristics, the monitoring and evaluating changes in human gait reveal important information about quantitative objective measurement of the different gait parameters and about the evolution and early diagnosis of different diseases [2–7].

The purpose of this paper is to review the latest advances in technologies to assess clinical applications of wearable sensors for human gait analysis.

The gait alterations and disorders represent main problems in neurodegenerative diseases such as multiple sclerosis, Parkinson's disease, post-polio syndrome, brain tumors, cerebrovascular pathologies, neuromuscular diseases, or in joints osteoarthritis. Multiple sclerosis patients present important gait alterations such as shorter steps, higher rhythm or lower walking free speed by comparing with the healthy subjects. Parkinson's disease is a complex neurodegenerative disorder characterized by various motor impairments, including tremor, postural instability, movement with low speed, resistance to externally imposed movements, a very serious difficulty in motor planning, action and execution of non-attention demanding tasks [7]. Brain damage is correlated with limited balance performance and increased step variability.

Musculoskeletal disorders are the most frequent causes for long-lasting or chronic pain and for restrictions on mobility and physical performance, leading, in the dramatic case, to an increased morbidity [8]; they affect hundreds of millions of people worldwide with very large increases expected by 2020, due to an increase of people over 50 years [8].

Osteoporosis is a disease characterized by lower bone

mass and deteriorated bone structure, and it represents a major problem related to gait and balance deficiencies. For osteoporotic people, the risk of fractures is increased and the falls represent one of the biggest risk factor [9]. Hip fracture is the most serious complication of osteoporosis, most common in older persons. Other studies have found excess mortality in hip fracture patients in the immediate post-fracture period [10]. The incidence of osteoporotic hip fractures is expected to increase over the next decades as the elderly population increases [10]. Immediately after the fracture, and also some years after a hip fracture, patients, both men and women, have a higher risk of dying compared to the general population regardless of age [10]. The greatest number of osteoporotic fractures occurred in Europe (34.8%). In the year 2000, the total disability-adjusted-life-years lost was 5.8 million, of which 51% were accounted for by osteoporotic fractures that occurred in Europe and the Americas [9]. In these cases, it is necessary, using wearable sensors, to monitor the gait and the changes of balance in the elderly in order to detect problems and prevent a fall.

The joints osteoarthritis, one of the major chronic diseases usually found in people of middle age and old age, affects a very large number of populations. Osteoarthritis is the fourth most frequent cause of health problems in women and the eighth most frequent cause in men. About 40% of all persons over the age of 70 are affected by osteoarthritis of the knee. About 80% of persons with osteoarthritis suffer from limited mobility [8]. About 25% of osteoarthritic persons can no longer perform the most important basic activities of daily life [8]. There are many causes of osteoarthritis: deviation of the mechanical axis in the frontal plane, sagittal joint misalignment, overweight, excessive sport activities, trauma, biological, menisci lesion, instability due to the knee ligament injuries. Joints osteoarthritis involves a degenerative process of cartilage in the joints leading to its loss [8]. This degenerative process is caused by obesity, by excessive physical activity, by joint trauma, immobilization or hypermobility. In the last stage of osteoarthritis disease, generally, a joint replacement is necessary. Total

hip replacement and total knee replacement are cost-effective treatments, reducing pain, increasing mobility, and improving the quality of life. It is estimated that, due to the dramatic increase of osteoarthritic cases, by 2030, in USA the primary total hip arthroplasties number will increase with 572 000 (about 174%), while the total knee arthroplasties will increase with 3.48 million procedures (about 673%) between 2005 and 2030 [11]. The number of hip revision procedures in USA will be double by the year 2026, while the number of knee revisions is expected to be double by 2015 [11].

Post-polio syndrome is a neuromuscular disease characterized by muscular weakness and pain, abnormal weariness and muscular atrophy, and caused by the viral destruction of the medullar motor neurons and by the chronic degeneration of the motor units' endings [12]. Major symptoms of post-polio syndrome are a severe weakening of the motor system and major disorders of walking activities.

The next section offers a brief overview of the wearable sensors that are commonly used in human gait analysis. They include inertial sensors, accelerometers, gyroscopes, magnetic accelerometer, goniometers, pressure and force sensors, electromyography sensors, etc.

Wearable sensors systems

Objectives of gait analysis techniques are based on the use of different devices to capture and measure information related to the various gait parameters [2]. The actual devices and techniques allow an objective and efficient evaluation of different gait parameters, providing specialists with a large amount of information on patients' gaits [2]. The technological devices used for human gait analysis can be classified in three different categories: those based on wearable sensors (WS), those based on non-wearable sensors (NWS) and those composed of hybrid systems based on WS and NWS sensors [2].

There is considerable interest in developing human motion capture technologies that can be used outside the clinic or laboratory environment. Such technologies would enable the measurements at home, at work, at hospital, in gyms, on the sport field or in each environment that presents interest for monitoring and evaluating the normal and pathological gait. WS systems make it possible the management of patients affected by movement disabilities, the motion-related clinical measures and rehabilitation outcomes measures to be acquired outside the laboratory in the patients' natural environments and capture information about the human gait during the person's everyday activities. They may improve the objectivity of the analysis through quantitative measures of the pathological events.

In last years, more and more people uses in their daily lives WS systems, because these systems may overcome the limits of the existing measurement systems, giving the opportunity to reach mid or long-term data recordings both in clinical and home environments with a non-invasive low-cost method, and they contribute to treating and preventing neuro-musculoskeletal diseases and enhancing mobility.

The WS systems use sensors located on several parts of the body, such as feet, ankles, knees, thighs, hips or waist. These include accelerometers, gyroscopic sensors,

magnetometers, force sensors, extensometers, goniometers, active markers, electromyography, etc. The most used wearable sensors are inertial measurement units (assembly of accelerometer and gyroscope) and goniometers. Characteristics of knee and trunk motion are the most frequent gait parameters for wearable sensing. Recent technological advances have produced sensors that are smaller, lighter, and more robust than previous versions [13]. The identifying movement disorders, improving walking stability, assessing surgical outcomes and reducing joint loading are the most important clinical applications of wearable sensors and acquisition data systems [13]. Using wearable sensing systems in human data acquisition present many advantages, as it is shown in [13]: transparent analysis and monitoring of gait during daily activities and on the long term; data gathering and monitoring in any place, indoor or outdoor of laboratory [13]. Simple systems made up of single accelerometer or single foot switch have been used to detect various spatiotemporal parameters, such as step count, stride length, cadence, and walking speed [14, 15], while more complex systems present in their structure a large number of accelerometers, gyroscopes, and magnetometers to measure joints and segments kinematics [7].

Advances in wearable technologies can enable more affordable and accessible health care by developing non-invasive measurement devices that can provide real-time feedback to health care providers and to patients and in their daily activities [16–23]. Recent advances in the fields of information technology, sensor networks and miniaturized devices allow the possibilities of new solutions for monitoring and take care of the elderly [19].

The measurement and communication in real time between wearable systems, patients and health care providers have significant effects on the quality of patient's life [20].

A large number of studies demonstrate the advantages, the accuracy and the validity of the wearable sensors in order to measure and analyze the different parameters of the normal or pathological human gait. The research works studied healthy subjects [15, 21, 22] or they were conducted to assess the outcome of surgical procedures [9, 10] or for identifying kinematic differences during gait for patient populations like osteoarthritic patients [23–30], patients with vestibular loss [31], patients with Parkinson's disease [32, 33], prosthetic patients [34], in comparison with healthy subjects.

The most analyzed parameters of normal and pathological human gait are the following: distances travelled (m), velocity (m/s), cadence (number of steps/s), gait phases, step length (m), step width (m), joints angles (degree), swing time (s) (time between the foot lifting moment and the foot touching moment), support time (s) (time between heel touching moment and toes lifting moment), electrical muscles activity (EMG), ground reaction forces (N), forces (N) and momentum (Nm) in joints.

Inertial sensors

Inertial sensors are one of the most widely used types of sensors in gait analysis. They are electronic devices used to measure angular velocity, acceleration, orientation, and gravitational forces for the studied subject [2]. Inertial

sensors are usually made by a combination of accelerometers and gyroscopes, but, sometimes, they also contain magnetometers. Gyroscopes are based on the property, which implies that all bodies that revolve around an axis develop rotational inertia [2]. MEMS (micro-electro-mechanical system) gyroscopes typically rely on the Coriolis effect to measure angular velocity. It consists of a resonating proof mass mounted in silicon. The gyroscope is, unlike an accelerometer, an active sensor. The proof mass is pushed back and forth by driving combs. A rotation of the gyroscope generates a Coriolis force that is acting on the mass, which results in a motion in a different direction. The motion in this direction is measured by electrodes and represents the rate of turn. In Figure 1, various inertial sensors are shown: angular rate sensors, multi-axial accelerometers, inertial measurements units (accelerometers and gyroscopes assemblies) (http://www.aptec.com/inertial_sensors.html).

Inertial sensors have initially used to analyze vibration and impact [35, 36] or movements at low velocities such as gait and running [37, 38]. There are a large number of studies that are based on the use of inertial sensors [15, 21, 22, 24, 34, 39–52]. The accelerometers are used in [33, 53], the gyroscope are used in [23, 33], and the magnetic accelerometer rate gyroscope are used in [21, 22, 39].

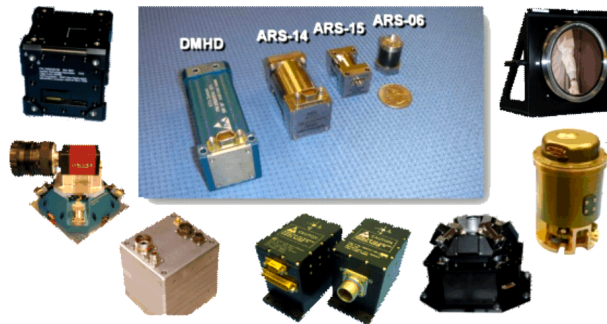


Figure 1 – Inertial sensors (http://www.aptec.com/inertial_sensors.html).

Wearable gyroscopes and accelerometers were used to detect differences in trunk sway angles between individuals with multiple sclerosis and controls [41] and between individuals with Parkinson's disease and controls [33]. In [7], a system for gait training and rehabilitation for Parkinson's disease (PD) patients in a daily life setting is presented. It is based on a wearable architecture aimed at the provision of real-time auditory feedback. The gait spatio-temporal features are extracted in real-time and they are compared with a patient's reference walking parameters [7].

A system with inertial sensors to quantify gait symmetry and gait normality was developed by authors in [42]. This system was evaluated in-lab, against 3D kinematic measurements; and *in situ*, against clinical assessments of hip-replacement patients, obtaining a good correlation factor between the different methods. Ferrari *et al.* presented an algorithm to estimate gait features, which were compared with camera-based gold standard system outcomes, showing a difference in step length below 5% when considering median values [43]. In [44], the authors 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 for subjects suffering of Parkinson's disease. The system was able to measure the acceleration of the patients during standing up and the necessary time from sit to stand period [45].

An inertial measurement unit was used to determine sagittal, coronal, and transverse ankle kinematic differences between individuals with ankle osteoarthritis and controls [24]. The miniaturization of inertial sensors allows the possibility of integrating them on instrumented insoles for gait analysis, such as the Veristride insoles, which additionally include pressure sensors designed for distributed plantar force sensing developed in [32].

In [46], the authors used three inertial measurement units to monitor sitting and standing posture and trunk, thigh, and calf sagittal plane kinematics during daily activities at home and in a clinic for individuals' undergoing rehabilitation. In [47], electrogoniometers and accelerometers were used to track knee flexion/extension angles throughout the normal workday including activities (Figure 2).

In [21], the authors assessed running kinematics *via* 12 accelerometer–gyroscope–magnetometer units, while subjects ran outside on a track. Movement data were recorded with ETHOS devices. ETHOS is the ETH Orientation Sensor, a customized inertial measurement unit for unconstrained monitoring of human movement.

Micro-electro-mechanical sensors can be considered as an alternative to high-speed optical analysis systems to measure dynamic movements [48].



Figure 2 – Wearable system [47].

A mobile measure device was developed to analyze the smash in a dynamic game, as badminton [49]. In this research, kinematic data of the arm and the racket were measured by inertial sensors, stored and transferred *via* Wi-Fi, while the shuttle velocity was determined by high-speed video analysis [49]. Inertial measurement units were used to detect knee flexion/extension and foot angle differences between subjects with hemiplegia and healthy controls [39] and to determine whether hip arthroplasty patients walked with compensatory trunk sway movements [26]. In [12] the authors studied four patients with post-polio syndrome using wearable components of the ECG/

ICG/3D (electrocardiography/impedance cardiography/three-axis) accelerometer system to evaluate the kinematical/energetic efficiency of a lower limb orthosis during a standard gait analysis protocol [12].

Goniometers

The goniometers are sensors that can be used to measure the angles of human joints, as ankles, knees, hips, metatarsals, but for other joints, too [27, 29, 30, 47, 50–54]. The goniometers could be: strain gauge-based goniometers, inductive or mechanical goniometers. Strain gauge-based goniometers (Figure 3) work with resistance that changes depending on how flexed the sensor is. When the sensor is flexed, its resistance increases proportionally to the flex angle. Dominguez *et al.* developed a digital goniometer based on encoders to measure knee joint position [55]. These sensors are usually fitted in instrumented shoes to measure ankle to foot angles [32].



Figure 3 – Various Biometrics Ltd. flexible goniometers – they have the same principle, but different dimensions, on depending of the human joints dimensions.

WS systems offer a convenient way to assess movement related aspects of surgical outcomes. For dissimilar total knee replacement prosthetic implants, flexible goniometers were used for standard and high flexion implants [29, 30] and gyroscopes were used for fixed bearing and mobile bearing implants [34]. Flexible electrogoniometry was used to quantify knee flexion/extension differences before total knee replacement surgery for osteoarthritic patients [28]. WS inertial sensors mounted on the shank and thigh were used to compare the kinematic before and after anterior cruciate ligament reconstruction surgery [56].

Ultrasonic sensors

Ultrasonic sensors measure the time it takes to send and receive the wave produced as it is reflected on an object. They have been used to obtain short step and stride length and the separation distance between feet [57, 58]. The measurement range of ultrasonic sensors varies between 1.7 cm and nearly 450 cm. In [19] the authors provide a telemeter system (Figure 4) embedded in clothes measuring certain mobility parameters for monitoring with very good precision the daily activities of the elderly in institutions or at home. The distances between the mobile node and three anchor points are provided by the time of flight measurement of the ultrasonic pulses [19].

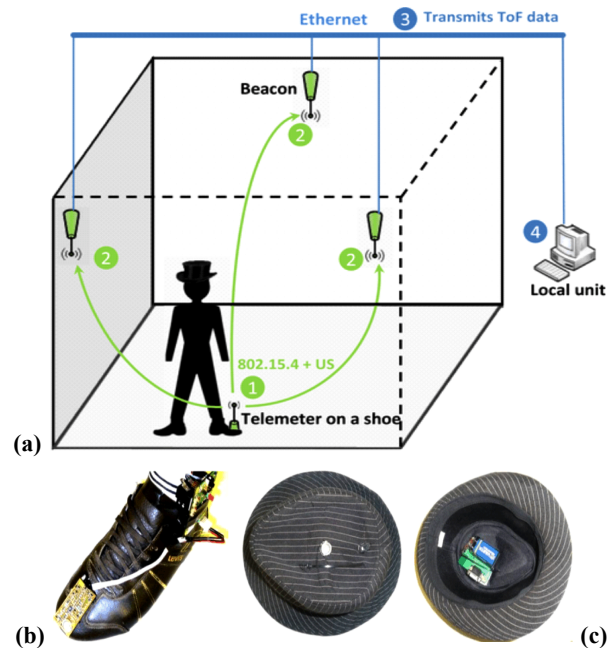


Figure 4 – (a) Telemeter system architecture; (b) Device embedded on a shoe; (c) Device embedded on a hat.

Pressure and force sensors

Force sensors measure the GRF (ground reaction force) under the foot and return a voltage proportional to the pressure measured. Pressure sensors [7, 32, 59–61] are usually used for measurement of foot plantar pressure distribution, gait phase detection and step detection.

The most widely used models of this type of sensors are resistive, piezoelectric, capacitive and piezoresistive sensors. The sensor is chosen depending on the range of pressure it offers, the range of pressure it will stand, linearity and its sensitivity. In the case of resistive sensors, their electrical resistance decreases as the weight placed on them increases.

The piezoelectric sensors present very good linearity and reactivity but they do not adapt to surfaces due to their large size.

The capacitive sensors are based on the principle that the condenser capacity changes depending on the distance between the two electrodes used.

In Figure 5, FlexiForce sensors are shown [59].



Figure 5 – FlexiForce piezoresistive pressure sensor [59].

This type of sensor is widely used in wearable gait analysis systems by integrating them into instrumented shoes (Figure 6) such as those developed in [60], or into baropodometric insoles [61]. In [62], the researchers have used an insole with 12 sensors and have obtained similar results for GRF with those obtained simultaneously in a clinical motion analysis laboratory.

By incorporating ultra-thin FlexiForce sensors into a “smart shoe”, known as the iShoe, to measure and analyze force distribution on a patient’s foot, the data can then be reported back to the doctor or to notify family members in the event of a fall [59].

An innovative system based on reflected light intensity was designed and presented by Lincoln *et al.* [63]. In their researches [29, 64–66], the authors have demonstrated that plantar pressure insoles provide sufficient data to estimate ground reaction forces (GRFs), center of pressure (COP), and ankle joint torques.

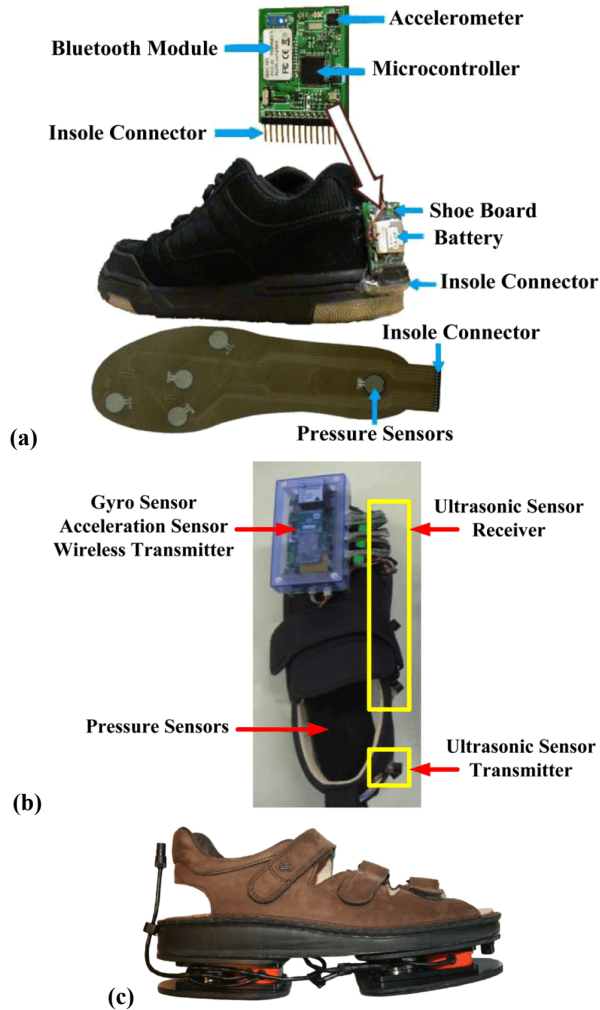


Figure 6 – Insoles sensors [61].

In Figure 7 are shown iShoe insoles produced by Tekscan Company, containing FlexiForce sensors to measure and analyze force distribution on a patient’s foot to prevent falls and assess balance problems [59].



Figure 7 – iShoes insoles contain FlexiForce [62].

Electromyography (EMG)

An important improvement of gait analysis science was obtained since the electromyography (EMG), the technique that measures voluntary or involuntary muscle contraction, as an electrical reaction, was introduced in walking study of healthy subjects and amputees patients [67, 68]. EMG has contributed in many clinical areas to improve the management of patients with neuromuscular disabilities: neurology, neurosurgery or orthopedics. The EMG could be non-invasively surface electromyography (Figure 8), or invasively with wire or needle electrodes. EMG is a very useful non-invasive technique used to understand the changes in gait function, gait phase detection, such as changes in paresis, spasticity [69], the knowledge of cerebral palsy [70, 71]. The collected signal is amplified and transformed in an appropriate format signal that could answers the clinical or scientific questions [2]. One of the most important contributions from EMG is the introduction of a new operation for patients with cerebral palsy [72, 73].



Figure 8 – Different types of wearable systems composed by EMG sensors and goniometers: (a) Biometrics [74]; (b) BioNomadix Wireless Wearable Physiology System [75]; (c) Delsys system [76].

Tanaka attached an EMG system to a user’s arm, which picks up electrical signals from their muscle movements (Figure 9) [77]. He uses biosensor technology to capture muscle data and translate it into electronic music [77].

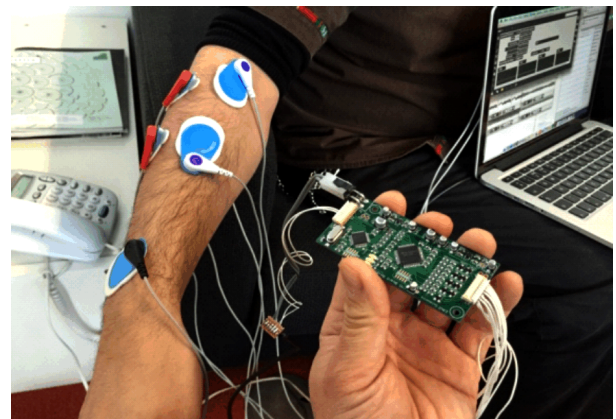


Figure 9 – Tanaka’s EMG system used to translate muscle data into electronic music [77].

Gait analysis systems

There are many commercial WS systems and NWS gait analysis laboratories, which use different combinations of the above-mentioned sensors and technologies. Successful gait analysis systems based on wearable sensors have been commercialized, such as the widely used Xsens MVN [78], which uses 17 inertial trackers situated in the chest, upper and lower limbs to perform motion capture and six degrees of freedom tracking of the body with a wireless communicated suit (Figure 10). MVN BIOMECH is an ambulant, full-body, 3D human kinematic, camera-less measurement system. It is based on MEMS inertial sensors, biomechanical models and sensor fusion algorithms. MVN BIOMECH is ambulatory, can be used indoors and outdoors regardless of lighting conditions. Results can easily be exported to other software applications.



Figure 10 – Commercial WS system based on inertial sensors: Xsens MVN [78].

Biometrics Ltd. is a world leader in the design, manufacture and distribution of technologically advanced sensors, instruments and software for the demanding needs in biomedical and engineering research [74]. Biometrics Ltd. data acquisition system based on electrogoniometers DataLog MWX8 is the latest in data acquisition technology for portable data collection and ambulatory monitoring on eight channels simultaneously in human gait, human performance, medical research, robotics [74]. The comprehensive range of Biometrics' goniometers and torsimeters are ideal for simple, rapid and accurate measurement of joint movement in multiple planes. The sensors, which are very robust, lightweight and flexible, can be worn undetected under clothing, without hindering the actual movement of the joint (Figure 11) [74]. Biometrics Ltd. range of Data Acquisition Systems collects both analogue and digital data from a wide range of sensors and is available in laboratory and portable configurations. An important benefit of Biometrics Ltd. systems is that they are designed to readily interface to

most video-based motion capture systems and other data acquisition instrumentation. This allows that the data to be synchronized and simultaneously collected from the sensors like: surface EMG, goniometers and torsimeters, accelerometer, force plates, myometer, dynamometer, pinch-meter, force sensors, load cells and contact switches [74] (Figure 12).

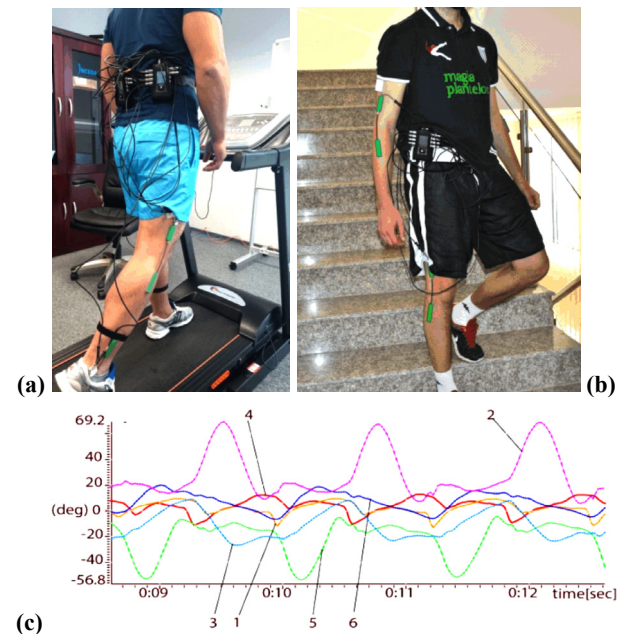


Figure 11 – Biometrics goniometers system mounted on subjects during experimental tests: (a) On treadmill; (b) On stairs; c) Diagrams collected from goniometers in real time.

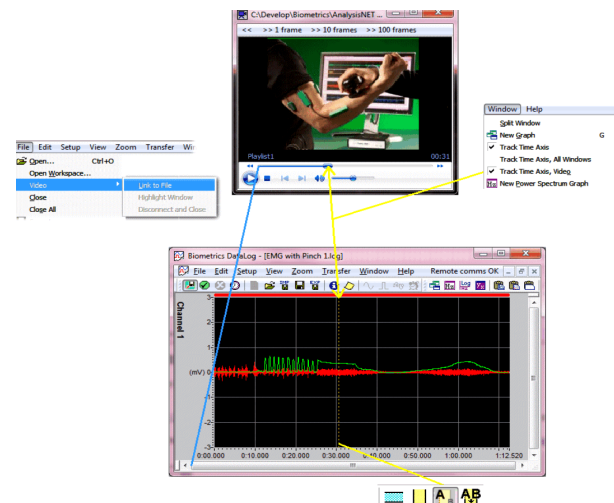


Figure 12 – Analyzed graphics obtained from electrogoniometers and EMG sensors, in real-time.

In papers [79] and [80], Biometrics data acquisition system and a set of goniometers were applied on hip, knee, and ankle joints to obtain the data for different diseases of patients or for healthy subjects, for the paretic and non-paretic leg of stroke patients.

The Xsens MVN BIOMECH is a full-body motion analysis system with 17 inertial motion trackers (MTx). Based on a biomechanical model, MVN BIOMECH provides 3D joint angles, body centre of mass as well as temporal parameters such as segment position, facilitating gait analysis. Using Xsens KiC algorithm, highly accurate

joint angles are provided, without the need for heading information, from magnetometers (Figure 13) [81].

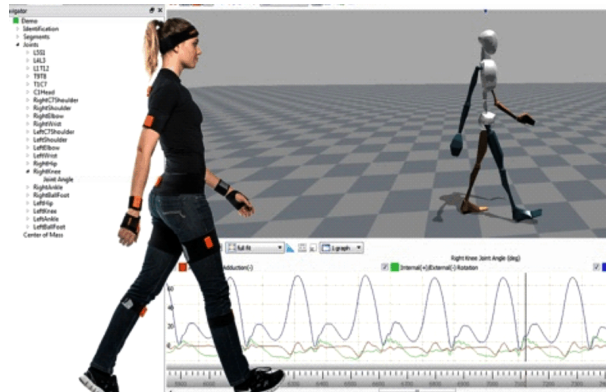


Figure 13 – Xsens MVN Biomech Link [81].

Researchers from Imperial College London and King's College London have studied and compared the anatomical joint angles collected by a portable system composed of inertial measurement units during stair climbing, to those joint angles acquired with an optical tracking device (Figure 14) [82].



Figure 14 – The portable system of inertial sensors mounted on a subject [82].

Another commercial package is the wireless M3D gait analysis system (Figure 15) developed by Tec Gihan Co. [83], which uses motion sensors on the lower leg, the thigh, the waist and the back and wearable force plates on the toes and the heels.

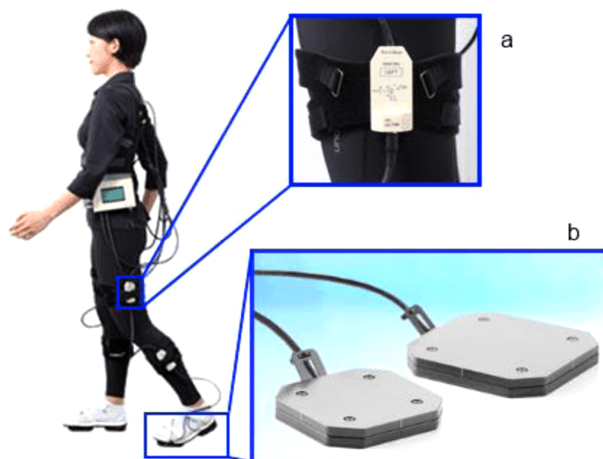


Figure 15 – WS system based on (a) inertial sensors and (b) wearable force plates. Tec Gihan Co. [83].

M3D force plates measure three component forces and three moments along three orthogonal axes and include an accelerometer, a three-axis gyroscope sensor and a three-axis geomagnetic sensor. A similar wireless system, composed of nine inertial sensors situated in the lower limbs and wearable force plates with wireless six-axis force sensors, was presented by INSENCO Co. under the name Human Dynamics Analysis (HDA) [84].

The design, implementation and testing of an integrated multi-channel AMLAB-based data acquisition, processing and analysis system is presented in paper [85]. AMLAB Workstation (AMLAB International, Sydney, Australia) is a new generation of highly integrated general-purpose laboratory instruments, which has been used in [86] and [87]. The system is developed to simultaneously display, quantify and correlate electromyographic (EMG) activity, resistive torque, range of motion, and pain responses evoked by passive elbow extension in humans. The resulting ranges of motion and torque data from the KIN-COM device were interfaced to an AMLAB workstation using appropriate Instruments.

The GAITRite1 system consists of a portable walkway embedded with pressure-activated sensors. Initial studies assessed the concurrent validity of the GAITRite1 system with single camera video-based systems and paper and pencil measures [88]. A subsequent study by Bilney *et al.* [89] reported high correlations between GAITRite1 and the Clinical Stride Analyzer1 for both spatial and temporal parameters. Using GAITRite1 system, gait variability has been suggested to be an important predictor of the risk of falling [90, 91].

The study [92] compared individual step and averaged spatial and temporal gait parameters (walking speed, cadence, step length and step time variables) measured with an instrumented walkway system (GAITRite1) and a three-dimensional motion analysis system (Vicon-5121), which recorded the motion of reflective markers attached to the subjects' shoes. GAITRite1 system is a valid tool for use in older subjects following knee joint replacement surgery.

Conclusions

Advancements in wearable sensors and wireless technologies determined a very important impact on health-care monitoring system. The main advantages of wearable sensors consists in the fact they are small in size, have low weight, power efficient and have wireless module for wireless communication. Wearable sensors systems may overcome the limits of the classical measurement systems, allowing to reach mid or long-term data recordings in clinical and home environments or in other environments like parks, stadiums, gyms. They are based on a non-invasive low-cost method and contribute to monitor patients' activities and daily routines, to treating and preventing neuro-musculoskeletal diseases and enhancing mobility, but also, they are used to monitor the training activities and the performances of the athletes.

Conflict of interests

The author declares no conflict of interests.

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