Toward an augmented shoe for preventing falls related to physical conditions of the soil

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***Abstract*—It is known that the physical conditions of an environment might represent an important risk of falling. In this paper, we report an ongoing project toward the creation of intelligent clothes aiming at preventing falls related to such conditions. The package described here is centered on an intelligent shoe. The developed prototype counts two main parts: hardware and software. The material is composed of a set of sensors and actuators, distributed in strategic positions of the shoe, while the software is a soft real-time system running on a Smartphone. Our prototype has been served for the differentiation of physical properties of soils (concrete, broken stone, sand and dust stone).**

***Index Terms*—Fall prevention, augmented shoe, smart shoe**

I. Introduction

Falls represent a major factor in the frail elderly. Beyond the physical injuries they can cause (fracture of the proximal femur), in many cases falls leave a psychological impact due to the fear of falling. All these factors can lead to a significant loss of autonomy. Such observations have contributed to the design and implementation of multiple programs dedicated to the prevention of accidental falls. Knowing that such a program has to include many risk factors in order to be effective: physical exercises, education, health "state controls" (orthostatic blood pressure, vision, hearing, balance and gait, drugs review, etc.) and environment hazards have been incorporated into multiple programs [1]. Thanks to recent advances achieved in many technologies, we would like to go a step further these approaches, by analyzing and exploiting the interdependence of several factors. For example, we know that the type of the ground that a person is walking on, may affect his/her balance [2]. Our research project aims at targeting these aspects.

By doing so, unlike traditional activities aiming at preventing accidental falls, we want to provide an on-site assistance to the user via different intelligent clothes. More particularly, our goal is to assist the user in situations where the physical conditions of his/her environment might represent a high risk of falling (slippery surfaces, steep slope, etc.). To this goal, we report here the development of an intelligent package centered on an augmented shoe. This prototype is composed of a set of sensors and actuators, distributed in strategic positions of the shoe, driven by a real-time system running on a Smartphone.

This paper presents the first prototype of the *ACHILE* (ACtive Human-computer Interface for Locomotion Enhancement) system. In a first experiment, while walking on several types of ground (concrete, broken stone, sand and dust stone), data collected via the sensors has served for the differentiation of the physical properties of multiple types of soils. In a next step, these results will serve for the determination of appropriate stimuli that should be conveyed via the actuators in order to provide an on-site assistance to the user.

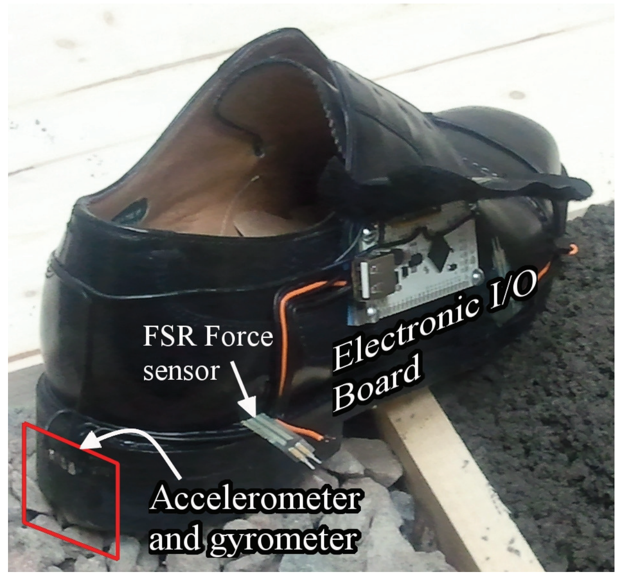

Fig. 1. Augmented Shoe Prototype

II. Related work

As shown in [3], over the past decade, several types of shoe or sole having data acquisition and/or vibration transmission capabilities have been developed. Nevertheless, much of these works has been designed for the rendering of symbolic information (i.e. directional indicator, encoded message) rather than conveying ecological stimuli [4]. In the field of interactive shoes, Paradiso et al. have proposed an instrumented shoe for acquisition of the gait while being equipped with a sound feedback for dance performances [5]. Samsung Electronics was also interested in dance training with his patent presented in [6]. Recently, an instrumented shoe dedicated to analyzing and maintaining the balance via a single-frequency vibrotactile feedback was presented in [7].

Instrumented shoe with wireless capabilities demonstrates the feasibility of computing walking parameters such as heel-strike, toe-off, foot orientation and position [8]. Some factors associated to a risk of fall were analyzed and a risk factor index was computed with eight walking parameters such as pressure correlation, step time, cadence and stance-to-swing ratio [9]. Nevertheless, in these previous works, the computation of the balance did not take into account everyday life activities of the user, medication and environmental perturbations [10]. The environmental perturbation considered in this paper includes the physical properties of the soil.

In the work described in [11], similar methods combined with an artificial intelligence module, were used to compute the balance of the user. In the patent described in [12] such a system is used in order to automatically detect a fall and notify the accident to a health care professional via an internet connection. Other interactive systems exist. For example, the one detailed in [13] provides a support system for athletes training. This product does not analyze the posture, but evaluates whether the energy of the athlete is spent adequately according to the type of ground. In [14], "Early Success Inc." details an application for the correction of children gait. This work targets defects such as toe-walking. A beep indicates an error in the gait in a manner similar to the proposals of [5]. The latest patents of "Adidas International Marketing" discusses mechanisms that automatically adapt the stiffness of the sole according to the activity: [15], [16]. The actuator of the mechanism helps at adjusting the physical characteristics of the sole namely its stiffness and its damping. Posture and balance are modified according to the realized adjustment, but this patent does not present any algorithm for recovering nor analysing the balance.

As seen through this brief review, different types of shoe and sole were developed through multiple technologies. In the system that we describe here, we propose a new approach that combines several of these technologies in order to prevent falls related to physical conditions of the soil.

III. Proposed system

The *ACHILE* system contains several sensors and actuators. The package described here is centered on an intelligent shoe which is also used in serious game such as training balance control over different types of soil [17]. This is one of the components of the intelligent clothes. The developed prototype counts two main parts: hardware presented in subsection III-A and software in subsection III-B.

A. Hardware

With the first *ACHILE* prototype, we want to arrive with a system that will provide an on-site assistance to the user. Considering that balance and gait are dependent on physical characteristics of the soil [2], it is important to provide a support adapted to the type of soil. To achieve this goal, in addition to measures relating to gait, it is therefore crucial to detect the physical characteristics of the soil. Knowing that the foot and the hip movements are important factors in the gait, we inserted several sensors in a shoe (see Fig. 2). In other words, some sensors are used for measuring physical properties of the environment while other help at computing gait parameters.

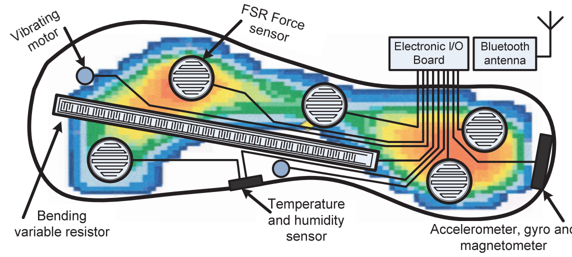

Fig. 2. Repartition of the the sensing and actuating devices in the sole.

- **The shoe and its sole.** The utilized shoe has no specific characteristic except that his heel should be at least as stiff as the harder material to identify. In other case, the measurement will be coupled with the heel deformation.
- **The accelerometer and gyrometer**
  The accelerometer is inserted in the hardest part of the heel (see Fig. 1). It provides useful information about the movement of lower limbs. On the other hand, since vibrations have been widely exploited for soil identification in planetary exploration rovers [18], they can serve the same purpose in this system. In other words, we assume that for soils having different physical characteristics, different vibrations should occur between the sole of the shoe and such grounds. It is in this state of mind that we used the accelerometer to measure these vibrations. The experience described in Section IV, will evaluate this hypothesis.
- **Force sensors.** The force sensors capture the interaction between the foot and the ground. This information is an input to the computation of gait parameters such as center of mass (COM) and center of pressure (COP). Both positions of COM and COP determine the stability of the user's gait.
- **Temperature and humidity sensors.** Gao et al. emphasized that the glaze ice was causing a high percentage of falls due to the thin layer of water located on their surface [19]. Because of such an observation, we inserted a temperature and humidity sensor into the shoe.
- **Auditory/vibrotactile/visual actuators.** Various studies have shown that sending appropriate stimuli could correct sway in the gait and posture [20], [16]. Based on the theory that a certain level of noise can enhance the detection and the transmission of weak signal [21], vibrotactile signal send to the somatosensory system has demonstrated an improve on the balance [22] and on the gait [14]. In the same way, it has been proved that various stimuli can be used in order to correct the gait [22] and prevent falls [23]. For this reason, we want to transmit stimuli to help the user to correct abnormalities in his/her gait that can lead to a fall. These stimuli can be auditory, vibrotactile and visual as proposed in [24]. They will be transmitted via the actuators inserted in the sole shoe, at the hip (from the smartphone), and some LED located in the glasses.
- **The electronic board.** These sensors are acquired with an

electronic board which contains an ADC (analog to digital converter) and Bluetooth capabilities. The microcontroller on the electronic board embedded in the shoe is a PIC24 from Microchip. Signal waveforms are transmitted via the Bluetooth (local telecommunication) to an Android Smartphone where the data is logged and analyzed in real-time.

B. Software

Data coming from the shoe should be treated in order to provide appropriate assistance to the user. This treatment is provided through a software component running on the Smartphone. Here, we used a Galaxy 10.1 tab containing the Android O.S. 3.2. Based on collected data, this software module, which some components are shown in Fig. 3, aims at determining if a situation seems to present a certain risk of fall for the user. This module includes:

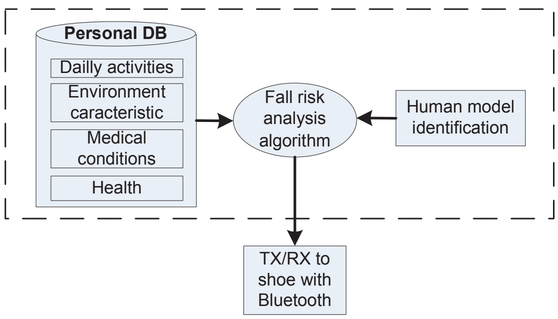

Fig. 3. Components of the software.

- **A database.** This database contains personal information of the user. It contains information that will be exploited in order to provide a personalized assistance to the user. In addition to data coming from the shoes, the database contains data on: fear of falling [25], daily activities of the user, his medical condition [26], [27], physical characteristics of its usual environment, characteristics of its lower limbs (morphology) and its gait model (parameters) on different types of ground [2].
- **Extraction of gait parameters.** Some studies suggest that the ability to reproduce reliably a gait pattern is related to the risk of falling [28]. Temporal measure seems to be a good measure of the risk. These temporal measures are stride, step, stance, swing, and double support time. Other measures could be step length, stride length, cadence (number of step per second), stance-to-swing ratio, pressure correlation under the foot [9] and postural sway [29].
- **A model of the walking dynamics.** This model allows determining the kinematics and dynamics of the gait. In particular, it assesses whether the barycentre of the human body observes a balance similar to that of an inverted pendulum. Indeed, generally this barycentre should oscillate between the step and the stride in a way to respect the stability measures described in [30].
- **Classification of user activities.** Automatic recognition of physical activity was previously investigated using Support Vector Machine (SVM) classification [31]–[34] and Fast Artificial Neural Network (FANN) classification [35]. In particular, fall detection was also investigated using only the accelerometer in a cell phone [36]–[38].
- **Fall-risk analysis algorithm.** This algorithm is the bond that units the database to these three algorithms: extraction of gait parameters, walking dynamics and classification of user activities. Its role is to assess the risk represented by a given situation. In this paper, this algorithm is mainly used to differentiate the physical characteristics of soil. The dynamic stability effect of compliant surface on the gait has already studied in [39]. Our algorithm implemented in the shoe differentiates the type of soil for a better risk evaluation.

IV. Experimental results

The proposed system aims at assisting users in situations where physical characteristics of the soil may present a certain risk of fall. In order to provide such assistance, it is essential to differentiate the types of soil one from each order. Knowing that vibrations are often used in order to differentiate soils, we hypothesis that the vibrations measured by the accelerometer inserted in the shoe will also allow us to differentiate soils. Here we describe the experiment conducted in order to evaluate this hypothesis.

Hypothesis. We know that the type of a soil may affect walking [2], we hypothesis that this difference should be reflected in terms of vibrations that occur between the sole of the shoe and the ground. Therefore, using the accelerometer, we should be able to measure this difference. In other words, using our augmented shoe, we will be able to differentiate from grounds having different physical properties.

Apparatus: types of soil. For this evaluation, three granular materials (deformable) and concrete (non-deformable) are used as types of ground. The three granular materials are broken stone, sand and dust stone: they are represented in Fig 4.

Experimental procedure. A 67 kg man, for who the shoe has been designed, did wear the shoe for the experiment. On each surface, he realized about thirteen steps one after the other. During this experiment, for each step we recorded the force located at the heel, the bending of the sole and acceleration at the heel. Thanks to the speed of the electronic board and our application, these measurements are collected at a sampling frequency around 1000 Hz which is enough for measuring ground reactions and vibrations.

Results and discussion. For the first five steps, Fig. 5 shows the data recorded by the sensors. Starting from the top of this figure, the four first graph shows the acceleration waveforms logged for each type of ground. The two others show the heel force and the bending of the sole. Looking at the heel force, we observe that his extrema correspond to an equivalent extrema in the acceleration graphs. This let us understand that the data coming from the accelerometer is directly related to the steps performed by the user.

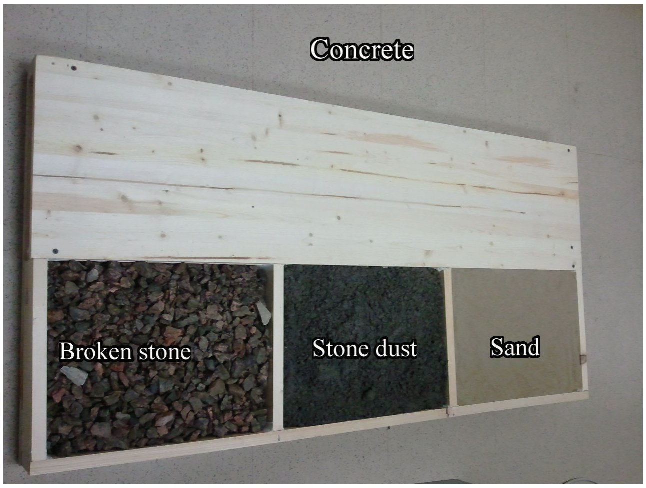

Fig. 4. Test bench for an evaluation of the shoe

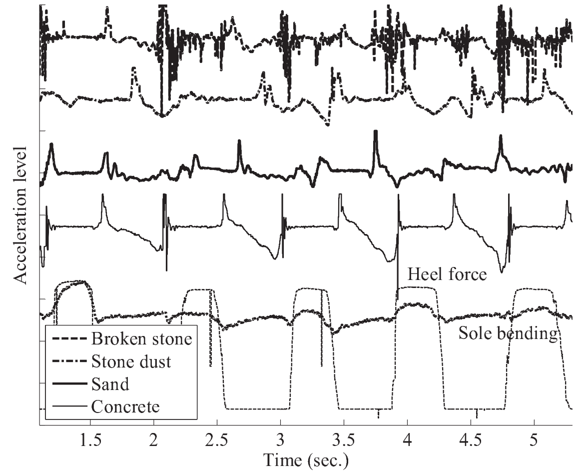

Fig. 5. Measurement and signal waveforms for each material

Looking at the acceleration graphs, quickly we notice a clear difference between these four. This difference is explained by the fact that the vibrations measured by the accelerometer represent the variation of the soil deformation under the impact force between the shoe heel and the ground. These variations are directly related to the physical properties of the soil. For the three deformable grounds (composed of multiple grains) these properties are characterized by different parameters. For example, one can quote: the size of a grain and its geometry, the grain density (space available between the grains) and the corresponding rheological model of the soil. All this explains the differences observed between the three first graphs. As opposed to the others, the concrete is a non-deformable ground. We thus understand that the vibrations corresponding to the impact between the heel and the concrete are different from the previous ones.

A better understanding of the acceleration waveforms needs an insight of the humain gait. Human gait is usually composed of two periods in one cycle of walking: *stance phase* and *swing phase*. During the stance phase, the muscles are solicited for maintaining balance while during the swing phase, the leg accelerates forward in front of the walker like a double pendulum. The *double stance support* occurs between the transition from the stance phase to the swing phase; it represents about 10% of the walking cycle. This name comes from the fact that both feet support the whole body. A walking cycle begins by a double stance support and contains another one after 50% of the cycle. The vibration of the ground is coming from the first heel strike at the beginning of the stance phase. This stance phase has a duration of approximately 60% of the walking cycle. It may be divided into three parts: the first heel strike on the ground (the *contact* in the initial double stance support), the *midstance* and the *propulsion* where the toes apply a force to the ground.

To get more details about each type of vibration, the waveforms have been treated in a four steps process. The first one consists at finding the beginning and the end of each frame. Each frame corresponds to approximately a second of acquisition associated with the stance phase duration. Since the duration of the stance phase may vary between gait steps, the number of acquisition points is not determined. Thereafter, zero padding is added at the beginning and at the end to obtain 2^n data points then a hamming window is applied on the signal. In a last step, this signal is finally filtered with a Savitzky-Golay (polynomial) smoothing filter with an order of 21 and an analysis of 43 data points.

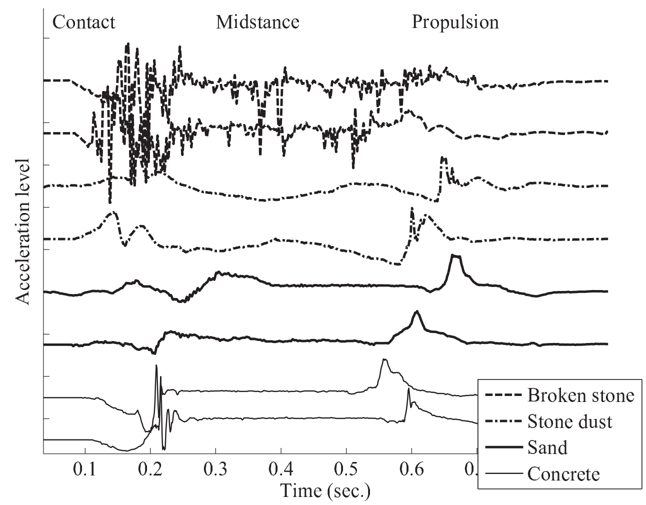

Fig. 6. Some acceleration waveforms after signal processing

The previous analysis can be exploited in determining an algorithm that can serve for the identification of each type of ground. Nevertheless, at the current step of our research, we are not interested in this issue; this will be addressed in a future work. The three stance parts are clearly identified on the Fig. 6. This experiment has served for the validation of our hypothesis. Indeed, the waveforms observed in Fig. 6 clearly exhibit different waveforms of vibrations for the different types of grounds.

V. Conclusion

This paper described an intelligent system aiming at providing on-site assistance to users. This system is centered on an augmented shoe containing several sensors and actuators. With the realized experiment, we showed that the use of an accelerometer can serve for the differentiation of several types of grounds (concrete, broken stone, sand and dust stone). Unlike rovers, classification of terrain is different for a walker. We have to consider the gait of the walker. The originality of the research work is therefore the analysis of acceleration waveforms during the stance phase and more particularly during the heel strike.

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