Design and Implementation of a Low-Cost Mechatronic Shoe for Biomechanical Analysis of the Human Locomotion

P. Boscariol, A. Gasparetto, N. Giovanelli, S. Lazzer and L. Scalera

Abstract In this paper the development of a low-cost and easy wearable mechatronic system for the measurement of ground reaction forces (GRF) for the biomechanical analysis of the human locomotion is presented. The system consists of an insole, a conditioning device for the signals produced by the sensors applied to the insole and a data acquisition system connected to a USB portable storage. The sensors applied to the insole can measure the reaction forces in the horizontal and vertical directions during locomotion. The prototype was validated by comparing the data from the sensors with the values obtained using a force platform.

Keywords Mechatronic shoe · Biomechanical analysis · Human locomotion · Ground reaction forces · Sensors

1 Introduction

This work is part of a project carried out by an interdisciplinary team composed by researchers in Mechatronics as well as Biomedical Science. The aim of this study is the design and the implementation of a low-cost mechatronic insole, provided with sensors, to be inserted in a shoe, in order to measure horizontal and vertical ground

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reaction forces (GRF) during locomotion (running or walking). GRF analysis is also used by athletic trainers in order to study the running performances of the athlete, by providing the possibility of intervention with specific training focused on improving the running efficiency [9–11, 17, 18, 23].

Nowadays it is possible to find systems, which can detect this kind of information, such as force boards, barodometric plates [7] and insoles equipped with sensors. Ground reaction forces are often investigated in biomechanical studies on the human gait [1, 4, 5, 12, 13, 15, 22]. The analysis of these forces plays an important part in medicine during rehabilitation of patients hit by stroke [8] or for people with diabetes, in order to prevent the occurrence of ulcers on the foot. For example, instrumented shoes with a thin layer of strain gauge transducers [6], or piezoelectric copolymer film [19] or two sensors mounted beneath the forefoot and the rearfoot [16] have been built. However, these devices turn out to have a high cost and to be very cumbersome. Moreover, they greatly increase the thickness of the sole, as well as its weight, thus altering the correct gait [24].

The first studies on the motion analysis coincide with the birth of photography, because if it was possible to represent reality on a photographic plate, it would have been possible also to develop devices capable to take a series of pictures over a short period of time in order to record the motion. Subsequently, better results have been obtained by means of different cameras, which could capture the motion thanks to specific markers applied on the body of the person.

Nowadays, different technologies and methods for the biomechanical analysis of the step, in running or walking subjects, are available. The cheapest and most popular are based on software packages for the kinematic analysis, which allow to study the human motion by means of properly recorded video files. More information could be obtained from force platforms, which can detect the ground reaction forces in three directions. Different kind of devices, which provide useful information, could be integrated, such as accelerometers or gyroscopes, by means of which it is possible to calculate the external work by knowing the position of the Center of Mass (CoM). In the last few years, insoles that can provide the ground pressure of the foot [2, 3, 14, 21], considering the ground vertical reaction forces, have been developed. However, no similar system, which allows to obtain information on horizontal ground reaction forces, has been found in the literature. Measurement systems of horizontal reaction forces are still too cumbersome for a correct measurement during normal deambulation. To date, it is hard to record data during outdoor events, since installing force platforms on running tracks it is not always possible.

The paper is organized as follows: in Sect. 2 the design of the insole and of the accessory systems (data acquisition system, etc.), as well as the choice of sensors for the detection of horizontal and vertical forces, is explained. In Sect. 3 experimental results obtained from sensors mounted on the insole for a walking and a running step, as well as the comparison between these results and those obtained from a force platform, are described. In Sect. 4 conclusions are drawn.

2 Design of the Mechatronic Shoe

The CAD model of the insole was developed by means of SolidWorks™ environment. The resulting prototype was made of two half-insoles, which can slide one on the top of the other by means of guides. The prototype was designed so as to include the sensors for the measure of the reaction forces, namely five piezo-resistive sensors for the measure of vertical forces and a load cell for the measure of horizontal forces between the foot and the ground. The inserts for the five piezo-resistive sensors cables were built with the purpose of limiting the thickness after the components assembling (Fig. 1a). A prototype of the insole was realized by means of a 3D print, with a thermoplastic polyurethane elastomer 80 shore (TPU 80) printed with a 200 μm layer (Fig. 1b), which had a thickness of 7.8 mm and a mass of 0.175 g.

A piezo-resistive sensor is a kind of sensor made of a material that changes his own electrical resistance in proportion to the external force applied orthogonally to his sensitive surface. In this work Tekscan Flexiforce A401 sensors were used, in order to minimize the height of the insole and its total cost. Five sensors were positioned in coincidence of the first toe, the first, the third and the fifth metatarsus and under the heel, as suggested by [20]. With respect to other prototypes [8], bigger sensors have been used, because some preliminary experiments showed that with small sensors a more noisy signal was obtained.

The choice of the load cell turned out to be very complicated, considering the need to find a device that could be at the same time thin and robust: eventually, a Futek LSB200 load cell was chosen. Its dimensions are: 17 × 19 × 6.7 mm, and its thickness was considered suited to this application.

The data recorded by the load cell and the piezo-resistive sensors were registered at 1 kHz and logged into a portable acquisition device (MyRIO-1900 by National Instruments). The data acquisition software was developed in LabView™ environment. MyRIO was placed in a belt and powered by a 4 V batteries, which ensure the operation of the device for more than 2 h. So far, the capacity of the system is sufficient for the prototype-test phase, but in the future lithium-ion batteries with a larger capacity and a lower weight will be installed.

Fig. 1 The CAD model and the prototype of the sole with some piezo-resistive sensors and the I/O apparatus

Before every trial the sensors were calibrated using known weights. The calibration of the piezoresistive force sensors was performed after the sensors were fixed on the insole as suggested by the manufacturer.

3 Experimental Results

In order to verify the efficacy and the accuracy of the realized system, several experimental tests were made. The mechatronic shoe was worn by a subject, who was asked to walk on a Kistler force platform. Horizontal and vertical force signals obtained from the load cell and the piezo-resistive sensors were compared with those given by the platform.

The experimental were then post-processed with a dedicated program run in the MatLab™ environment. The program implemented a set of function for reading, analyzing and for graphically representing of data obtained from both the insole sensors and the force platform.

In Fig. 2 a typical trend of the forces measured by the force platform for one step is shown. The blue curve represents the trend of the vertical reaction force, in which the first peak matches the talon support and the second one to the forefoot. The red line represents the trend of the horizontal shear force, in which the first part corresponds to the braking phase and the second to the pushing. The green line, finally, represents the force perpendicular to the motion direction.

Experimental results are shown in the next figures. In Fig. 3 and in Fig. 4 two examples of vertical and horizontal forces measured by the sensors and the force platform respectively, in the case of a single walking step, are shown.

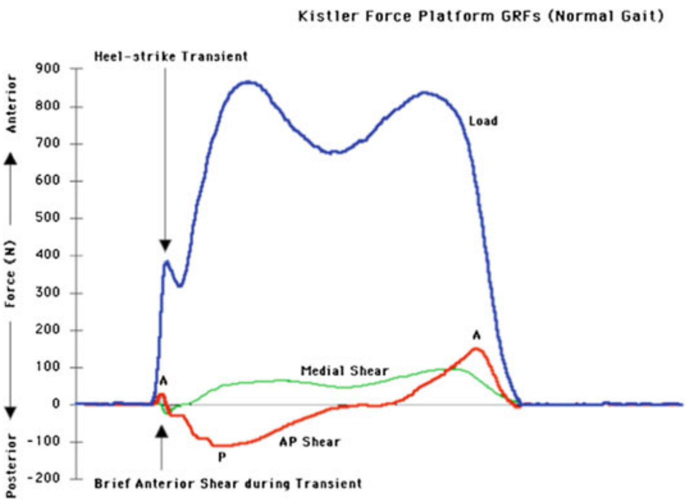

Fig. 2 Forces measured by the force platform for one step (normal walking gait)

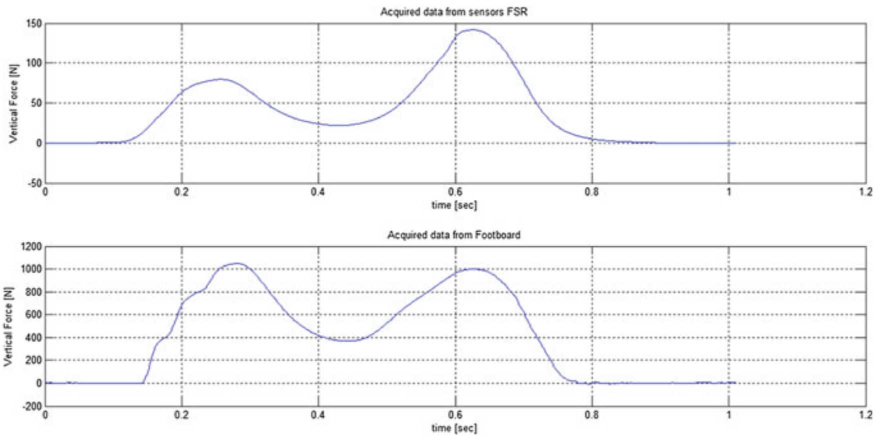

Fig. 3 Comparison of vertical forces during a step of walking (*top* piezoelectric sensors in the insole, *bottom* force platform)

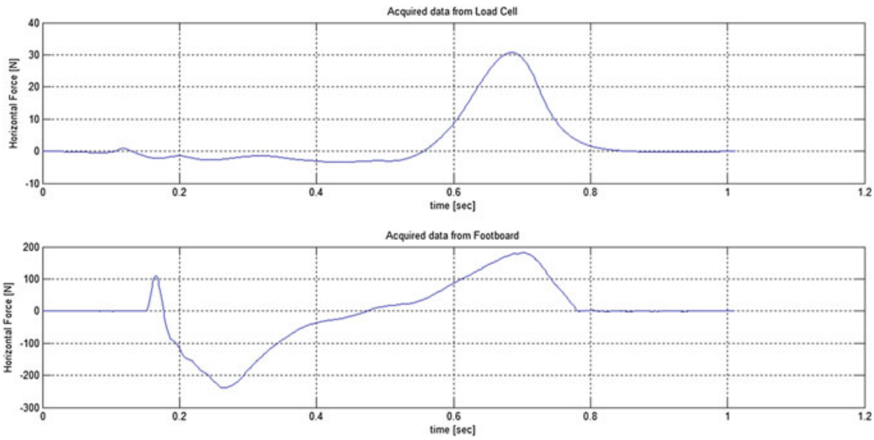

Fig. 4 Comparison of horizontal forces during a step of walking (*top* load cell in the insole, *bottom* force platform)

In Fig. 5 and in Fig. 6 two examples of vertical and horizontal forces revealed by the sensors and the footboard, in the case of a single running step, are shown.

The measurement of reaction forces gave satisfactory results, since it was possible to determine the contact times and the maximum force values determined from the insole sensors resulted very similar to those provided by the force platform. If we consider the shape of the signals, the trends of the vertical force during one step are quite close, even if the values are scaled. The offset resulting from the experiments was due to the difficulties encountered during the calibration phase, since the piezo-resistive sensors that were used turned out to be very sensitive with respect to

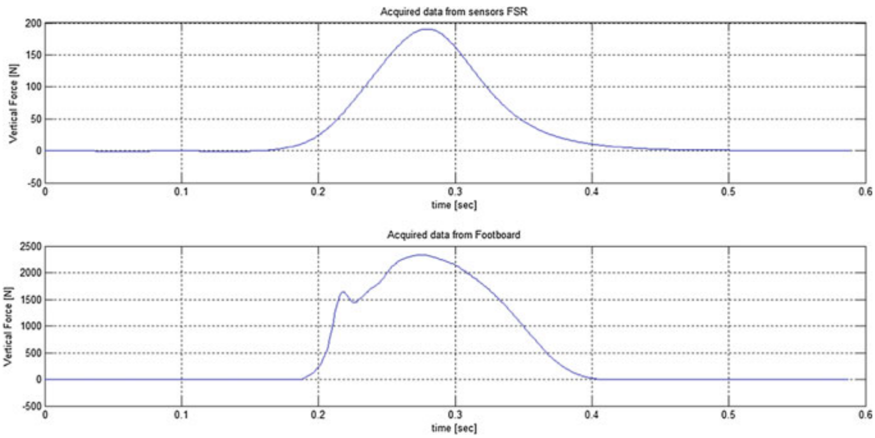

Fig. 5 Comparison of vertical forces during a step of running (*top* piezoelectric sensors in the insole, *bottom* force platform)

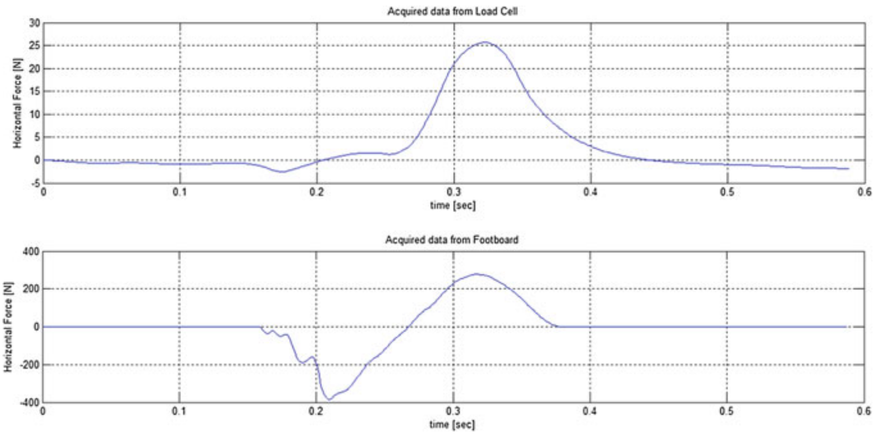

Fig. 6 Comparison of horizontal forces during a step of running (*top* load cell in the insole, *bottom* force platform)

the position to which the charge is applied. Indeed, every single individual distributes his load in a different way during the locomotion phase: therefore it is impossible to determine the optimal position to install the piezoelectric sensors in order to evaluate the vertical forces. Furthermore, a number of five sensors was not sufficient for a complete evaluation of the vertical forces involved.

Horizontal reaction forces gave more problems because from experimental tests it was not possible to find a perfect correspondence between the results obtained with the mechatronic insole and those obtained from the force platform. Namely, the peak related to the contact of the ball of the foot could be detected, whereas the peak related to the contact of the talon could not be clearly identified. This fact could be due the structure of the insole: since the insole is placed inside the shoe, it moves adequately with the foot during the step phase but during the braking and pushing phases the sliding between the two semi-insoles is restricted.

4 Conclusions

In this paper, the development of a low cost and easy wearable mechatronic insole, which could be integrated inside a shoe during outdoor events, for the study of ground reaction forces in both horizontal and vertical directions, was presented.

The efficiency and the accuracy of this mechatronic system were tested by comparing the results obtained the sensors mounted on the insole (a load cell for the measurement of the horizontal force and five piezo-resistive for the measurement of the vertical forces) with the data obtained from a force platform. The experimental results pointed out that, while vertical forces were detected with good accuracy, for the horizontal forces it was not possible to find a perfect correspondence between the results obtained with the mechatronic insole and those obtained from the force platform. In other words, the peak related to the contact of the ball of the foot could be detected, whereas the peak related to the contact of the talon could not be clearly identified. Therefore, future work will be done, in order to improve the accuracy of the results given by the load cell, mainly by studying a design of the insole which is optimized with respect to this goal.

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