A Novel Wireless Instrumented Shoe for Ground Reaction Forces Analysis in Humanoids

Abstract—**The measurement of ground reaction forces (GRFs) is crucial in the biomechanical analysis of gait and other motor activities. Current humanoid robots mimic some of the biological adaptation methods found in humans. Therefore, studying the GRFs in these robots allows not only to improve their overall performance, but also to extrapolate possible techniques for human walking rehabilitation. The balance of a humanoid robot may be compromised when it walks and, even more, when it walks across multiple grounds with different frictions. This paper presents a system to be seamlessly installed on a walking humanoid robot to measure normal and tangential ground reaction forces. The proposed solution is a cost-effective, lightweight and wirelessly instrumented shoe (ITshoe) for real-time measuring of the GRFs.**

Index Terms—**Force sensors, Ground reaction forces, Humanoid robot, Instrumented shoe.**

I. INTRODUCTION

Walking robots compete to mimic some of the biological adaptation methods found in humans. Studying these humanoid robots grants the possibility to deduce methods for human walking rehabilitation. During walking, the impulsive force between the stance foot and the ground may affect the stability and reliability of biped robots seriously. Bearing in mind the need to reach a properly and safely humanoid robot locomotion, with a precise and robust control, it is crucial to measure the contact force between its feet and the ground.

This work is part of a project entitled ”Automatic adaptation of an humanoid robot gait to different floor-robot friction coefficients”, that aims to achieve adaptive humanoid robot walking through several types of floors. Following this idea, the principal aim of this work is the development of a system capable of detecting and analysing the complete ground reaction forces (GRFs). The major requirements for such a system are small weight and size, self-contained and no impediment of functional mobility.

The current work presents a novel instrumented shoe (ITshoe) capable of measuring the three components of the GRFs. The solution detects and wirelessly transmits the GRFs in real-time, it is customizable for different robots, it allows more parameters than integrated solutions in robots, and it can be easily installed independently of the robot control. The ITshoe is designed to be used with the humanoid robot NAO and has two main parts: Outer Shoe (OSh) and Inner Shoe (ISh). The OSh is the instrumented part of the shoe, whereas the ISh is the link between the robot's foot and the OSh.

The remainder of the paper is divided as follows. Section II presents a review of modern developments connected to this work, such as commonly used sensors and existing instrumented systems. The developed prototype is presented in Section III. The system's architecture is outlined in Section IV. GRFs experiments and results are discussed in Section V. Finally, Section VI presents the conclusions and future challenges.

II. RELATED WORK

Multiple systems have been developed for GRFs estimation, being commonly used in two major fields: robotics and biomechanics. Most of today's humanoid robots are equipped with force sensing capabilities at the feet for stability purposes, based on commercial or custom-made solutions. Besides being expensive, commercial solutions adopted are tailored to specific needs in which the main concern is to provide an accurate estimate of the robot's center-of-pressure (CoP). Kim *et al.* [1] developed an intelligent foot for a humanoid robot using two manufactured six-axis force/moment sensors (twelve sensors). The developed foot operates similarly to a human foot, but it turns out to be a little unpractical and an expensive solution, since it requires a challenging process to be used with existing humanoids. On the other hand, Şafak *et al.* [2] use four force sensitive resistors (FSRs) to build a foot contact sensor for a biped robot. Although, no trials have been performed, over numerical simulations the authors achieved a viable method to monitor postural stability of biped robots.

Systems that allow quantitative analysis of human gait are normally classified into: ground mounted force platforms and wearable instrumented systems (e.g. shoes and insoles). Force plates have the disadvantage of limiting the number of steps that can be done and are expensive, hence, the increasing advantage of using portable instrumented systems. These systems are usually designed with strain gauges, piezoelectrics, force sensitive resistors (FSR) or 3- to 6-axis transducers. Different wearable systems have been designed and developed over the recent years in order to measure the GRFs, to estimate the coordinates of the CoP and to monitor gait events (see for example [3]–[6]). However, most of the solutions are designed to be used directly with humans, and few allow the measurement of the complete GRFs.

Zhang *et al.* [6] features a fully-portable instrumented insoles capable of measuring spatio-temporal gait parameters and CoP trajectories during walking and running assignments, using a multi-cell piezoresistive sensor. Crea *et al.* [7] presents a pressure-sensitive foot insole for real-time monitoring of plantar pressure distribution during walking. The system includes 64 pressure-sensitive elements and a electronic board to acquire and transmit the data through bluetooth with a sampling frequency of 100 Hz. The proposed solution is developed to do a gait analysis based only on the vertical ground reaction forces (vGRFs) and the coordinates of the CoP. The estimation of the vGRFs showed a high qualitative correlation despite the significant difference in terms of actual values measurements against a force-platform. Lincoln *et al.* [8] designed a low-cost silicone insole capable of measuring the complete three dimensional reaction force vector. The developed sensor features a error within 10% and appears to have a temperature dependency. Many solutions within this theme are developed, but none seems suited to be adapted and used with different humanoids.

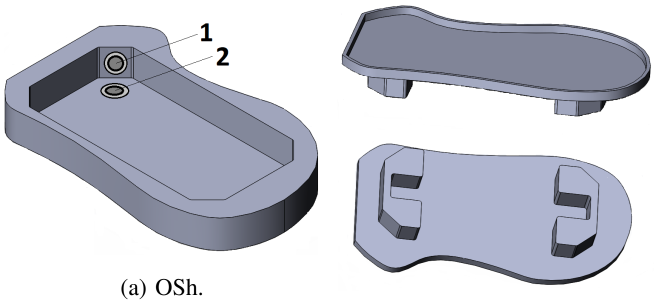
III. ITSHOE PROTOTYPE DESIGN

Fig. 1 schematically illustrates the design of the ITshoe. It has a total weight of 210 g (approximately 4% of the humanoid robot NAO weight) and dimensions measuring 125 mm × 65 mm × 18 mm to accommodate all the necessary hardware. The shoe is divided into two parts: OSh (Fig. 1a) and ISh (Fig. 1b). The OSh is the instrumented part of the shoe and the ISh is used to change the robot foot geometry allowing a tight fit with the robot's foot, thus ensuring a correct and complete force transfer between the foot and the OSh.

The building material used in the manufacture of the ITshoe is acrylic since it presents low density (1.18 g/cm^3) together with an acceptable modulus of elasticity (3.2 GPa). In addition, the acrylic allows the user to verify whether the hardware is well positioned after a specific experience, thanks to its transparency, and it is also an excellent electrical insulator.

A. ITshoe structure

The ITshoe presented in Fig. 2 is divided into three units: sensing, acquisition and streaming. The sensing unit is composed of piezo-resistive A301 flexiforce sensors (Fig. 2 block C, number 6): 4 with a standard force of 4.44N for the measurement of tangential forces (positioned at 45°) and 4 with a standard force of 111N to register the normal forces. The sensors have a reported typical linearity of ±3%, a repeatability of ±2.5% and a hysteresis of ±4.5% of the full scale output [9]. When compared to similar low price sensors (e.g. interlink FSR), they have a shorter response time, a better linearity, and offer the possibility of registering larger forces [10]. Over the sensitive area of these sensors is added a semi-sphere to ease the force transfer.



(a) OSh.

(b) ISh.

Figure 1: ITshoe model. The position of the force sensor that measures the tangential and the normal forces is represents by the numbers 1 and 2, respectively (left).

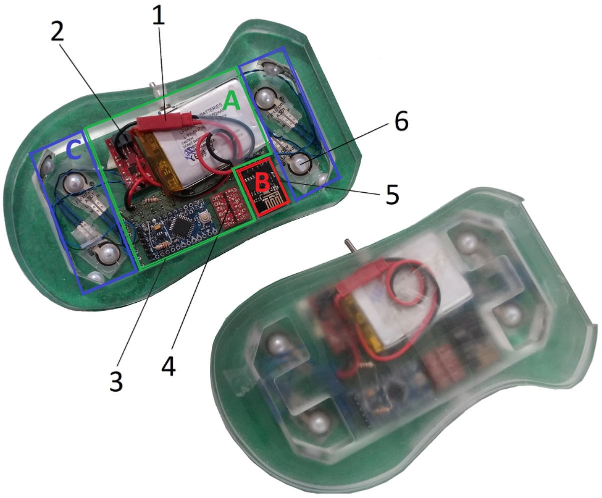


Figure 2: ITshoes schematic structure. The green block (A) is the acquisition unit, the red block (B) is the streaming unit, and the blue block (C) is the sensing unit. The main elements of these units are subtitled with numbers: 1–Battery; 2–Step-up voltage regulator; 3–Micro-controller; 4–Bi-directional level converter; 5–WiFi module; 6–Force sensor.

The acquisition unit (Fig. 2 block A) is responsible for the data acquisition. This unit deals with the electrical conditioning (Fig. 2, number 3 and 4) and the power supply (Fig. 2 number 1 and 2). The voltage dividers assembled in the PCB allow the connection of the sensors to the micro-controller. The ADC has a 10-bit resolution and 625 kHz frequency to convert the force signals into digital information. To synchronize and adjust the operating voltage level of this unit, a logic level bi-directional converter is used. The entire system is powered by a small 750 mAh Li-Po battery through a voltage regulator.

The streaming unit receives the data across a serial communication with the micro-controller and forwards it to the server, through the ESP8266 module (Fig. 2, number 5). The PCB added to the ITshoe incorporates a voltage regulator LM2937 to match the ESP8266 required power 3.3 V.

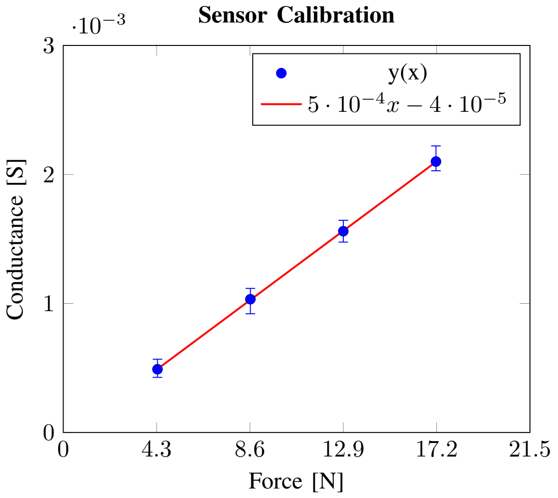


Figure 3: Force sensor calibration line.

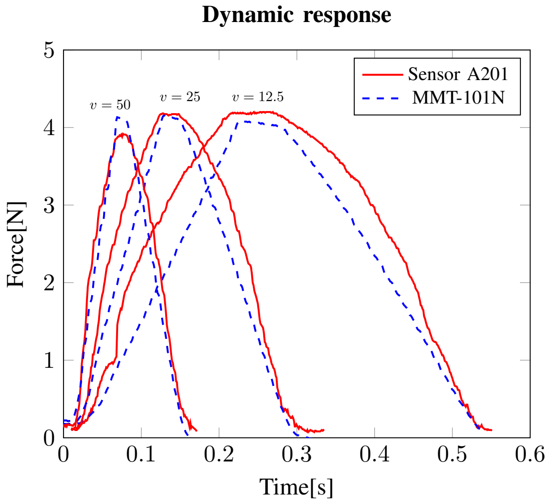


Figure 4: Flexiforce sensor dynamic response.

B. *Sensor calibration*

To ensure more accurate readings, a calibration procedure upon the sensors is required. The calibration procedure starts by conditioning the sensors and applying 110% (or slightly more) of the maximum test load onto the sensor for approximately 3 seconds. After repeating this conditioning process, different weights are applied on the sensor and, using a multimeter, the resistance is recorded. The plot in Fig. 3 shows the calibration line obtained for one of the 4.44 N standard force sensors, where it is visible that there is a linear evolution between the force applied to the sensor and its conductance.

Besides calibration, the sensors were also tested for their dynamic response. This concern occurs because the reaction forces that arise when a biped robot walks are variable, thus emerging the necessity to validate the dynamic response of the sensors. Hence, an experiment was conducted to analyze the sensors' dynamic response by using a mechanical testing machine Shimadzu MMT-101N. With this machine, a 4 N force was applied to the sensor with 3 different velocities (50, 25 and 12.5 N/s).

Fig. 4 shows the sensor responses for the applied forces. For the lower velocity, the sensor maximum force detected exceeds 3% the applied force, while for the higher velocity the sensor is not able to reach the maximum applied force (5.5% error). Indeed, there is a slight delay or saturation of the dynamic response of the sensors for some velocities, but those deviations are not expected to compromise the suitability of the sensors to monitor robot locomotion. Actually, and as might have been expected due to the piezoelectric nature of the sensors, their response improves with higher velocities, thus seeming quite adequate to catch the finer, or higher frequency, transitory force reactions.

IV. SYSTEM ARCHITECTURE

The proposed system architecture (Fig. 5) aims to create a data provider–data processor system in which the data provider is a measurer module responsible for measuring data regarding all components of GRFs for each robot foot separately. This module is also responsible for relaying this information to the data processor. The data processor is accountable for storing, processing and presenting such data.

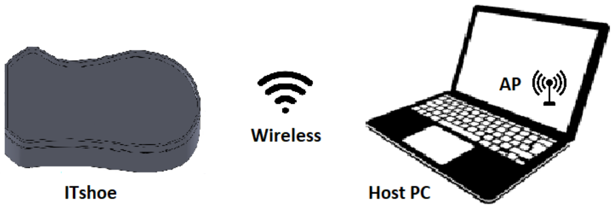


Figure 5: System basic architecture.

The data provider is assembled by two major modules: the control module and the capture module. The control module is responsible for all the initial settings required, from the time the data provider runs until it connects to the data processor. Firstly, starts by setting the WiFi module using AT commands. These commands allow the WiFi module to establish a connection with the data processor and further define the protocol as UDP. The capture module implements the capture process, being responsible for measuring data from all the sensors synchronously. The module operates based on a timer, ensuring periodic data acquisition for each sensor. The diagram in Fig. 6 illustrates the acquisition process.

The data processor is also formed by two major modules: the storage and the analysis modules. On the one hand, the storage module receives, stores, and displays the gathered data for further analysis. Essentially, in ROS environment, two functions (nodes) are used to receive and print the raw data. The data processor is configured to work as an access point (AP) creating a wireless local area network (WLAN). It waits for the ITshoe to be connected and starts receiving UDP

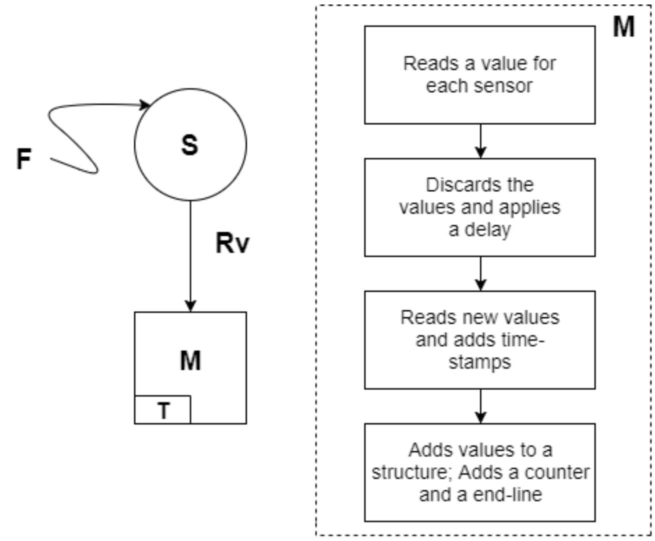


Figure 6: Acquisition process. F = Force applied to the sensor; S = Sensor; Rv = Resistance variation; M = capture Module; T = Timer.

messages. Well-formed messages are processed and made available for display, and also stored in a comma separated format file for further analysis by external applications. The second function subscribes the received message and generates a graphic environment (Fig. 7) that facilitates the understanding of the data evolution, as well as the CoP behaviour.

On the other hand, the analysis module implements a data analysis interface in order to convert the raw data into forces and to extract relevant information. The proposed system is designed to measure and transmit raw data at a frequency of 100 Hz.

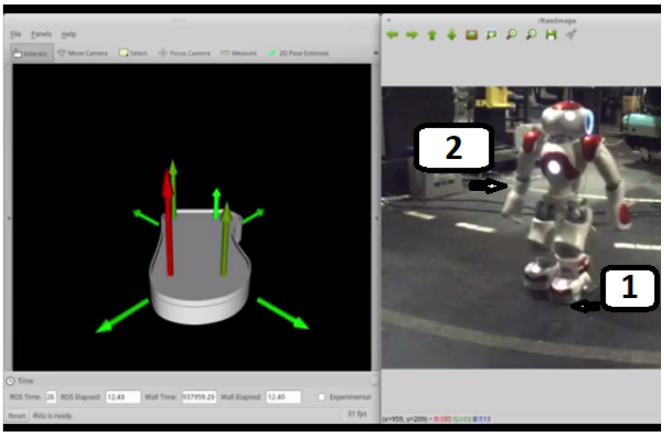


Figure 7: Graphical representation of the force values (example using the LITshoe). 1- ITshoes; 2- Humanoid robot NAO.

V. EXPERIMENTS AND RESULTS

This section describes the experiments and data acquisition results. The raw data upload rate is evaluated, and the GRFs are detected during two humanoid robot situations: static position and locomotion for two different grounds.

A. Data upload rate percentage loss

The ITshoes were turned on and data was collected for one hour; table I shows the data upload percentage loss for that time interval. By observing the results, it can be concluded that the developed ITshoes have a very good upload rate since the data loss is negligible. The loss of data can be justified with the instability of the WiFi module.

Table I: Data upload rate percentage loss for both ITshoes.

	Bytes sent	Bytes received	Data loss [%]
Left ITshoe	360000	359894	0.03
Right ITshoe	360000	359783	0.06

B. Detection of the vGRFs for a static robot position

Fig. 8 illustrates the position of the humanoid robot where the vGRFs (sum of the values measured by the four sensors responsible to measure this component of the GRFs) are gathered. As can be seen in Fig. 9, despite the visible differences between the total forces measured by the two ITshoes, the sum (53.19 ± 0.32) N ends up to be close to the robot weight: 5.4 kg, approx. 52.96 N.

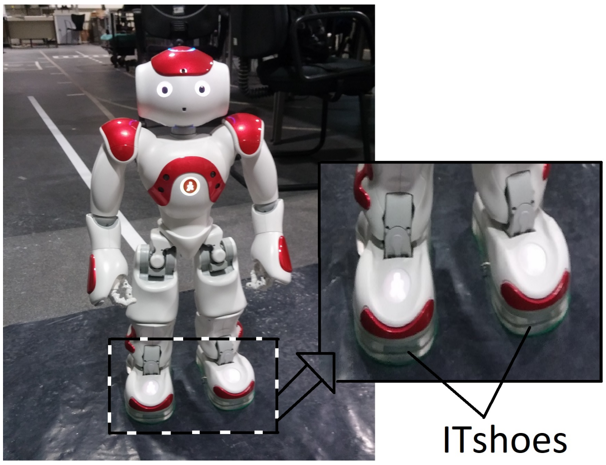


Figure 8: Robot in a static position.

C. Detection of the total GRFs during robot locomotion on two different floors

For this trial, the data is collected with the humanoid robot NAO walking on two different floors: laboratory floor and carpet. The total GRFs are divided into vertical ground reaction forces (vGRFs), and horizontal ground reaction forces (hGRFs). The measured vGRFs are illustrated in Fig. 10. In order to have a better perception of the measured values, only three random steps are shown.

It is noticeable that the step force patterns from grounds A and B are distinct. On the other hand, for each ITshoe (left and right) and type of ground (A and B), the step patterns are

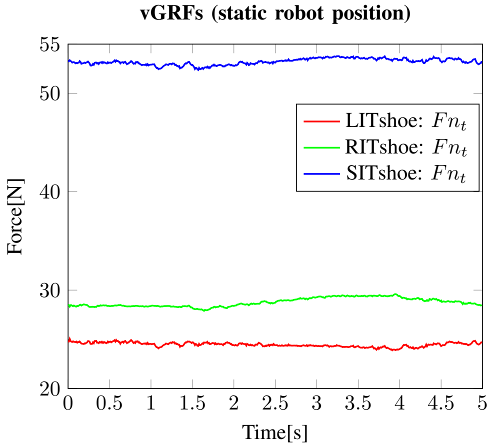


Figure 9: vGRFs for a robot static position. Left instrumented shoe (LITshoe) normal force (red), right instrumented shoe (RITshoe) normal force (green), and total (SITshoe) normal force (blue).

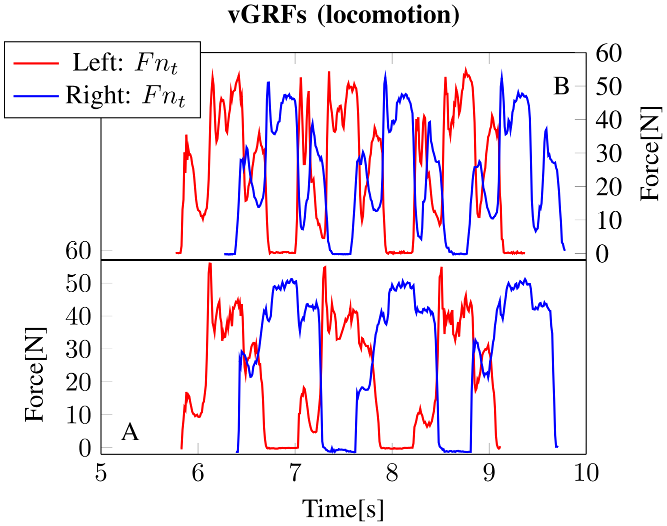


Figure 10: vGRFs for a walking humanoid robot on two different grounds. Excerpt of 3 steps for each ITshoe. A–laboratory ground; B–carpet.

visually quite similar among them. These observations are very interesting since they open the way for automatic detection of grounds based solely on the reaction force patterns. If precise absolute values for each foot are of concern, it may be required to have an additional calibration process by means of a ground truth source (e.g., a force-sensing platform).

The hGRFs can be represented in the sagittal and in the transverse axis as depicted in Fig. 11. Since the horizontal sensors are strategically positioned at 45°, it is quite simple to write the equations that represent the forces in these axis. The total horizontal force in the sagittal and transverse plane can be calculated as follows:

$$Fh_{st} = \frac{\sqrt{2}}{2}\left[(S1 + S2) - (S3 + S4)\right] \tag{1}$$

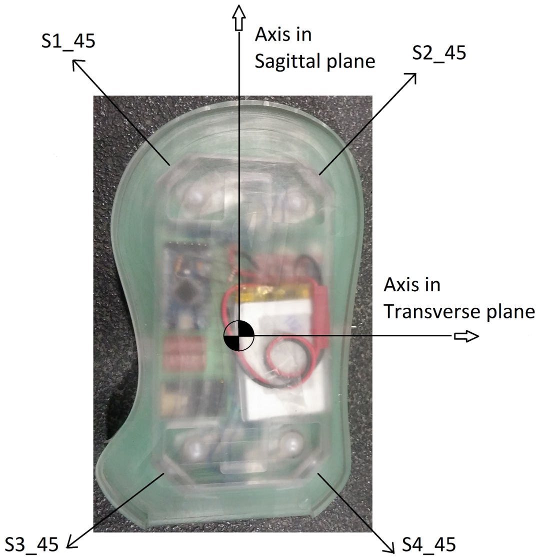


Figure 11: hGRFs axis detail. S1_45 to S4_45 represent the four horizontal force sensors.

$$Fh_{st} = \frac{\sqrt{2}}{2}\left[(S2 + S4) - (S1 + S3)\right] \tag{2}$$

where Fh_{st} is the total horizontal force in the sagittal plane, Fh_{tt} is the total horizontal force in the transverse plane, and S1 to S4 are the sensors used to measure the tangential forces.

Fig. 12 and Fig. 13 illustrate the hGRFs. The data corresponding to the moment when the foot is in the air (swing foot) was removed from the plots.

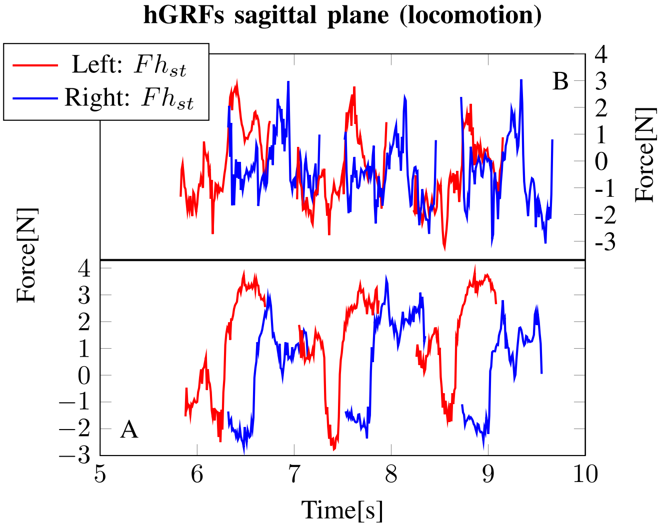


Figure 12: hGRFs in the sagittal plane for a walking humanoid robot on two different grounds. Excerpt of 3 steps for each ITshoe. A–laboratory ground; B–carpet.

Relatively to the hGRFs in the sagittal plane, a similarity between the data from the LITshoe and the RITshoe is visible for both grounds. This pattern may be useful to recognise different robot walking situations, since the robot balance will

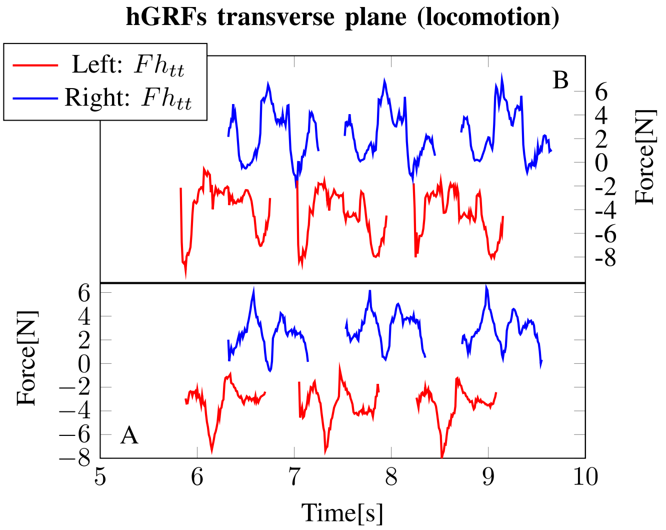


Figure 13: hGRFs in the transverse plane for a walking humanoid robot on two different grounds. Excerpt of 3 steps for each ITshoe. A–laboratory ground; B–carpet.

tightly affect these forces. The hGRFs in the transverse axis, between the LITshoe and the RITshoe, seems to be opposite but similar in absolute value. This behaviour appears to be correct since the positive direction in this axis for the RITshoe is the negative direction for the LITshoe as stated in Fig. 11.

All these indicators suggest that automatic detection of different floors, among other studies in gait analysis and expectedly also ground friction coefficients, can be done by observing the ground vertical and horizontal reaction forces using these instrumented shoes. Automatic separation of steps from full sequence of data is fairly easy since the alternation of the stance and swing foot is detectable by the activity of normal forces.

Anyway, with combined or separate steps, the next challenge is to process data and conclude about the floor the robot is walking on. Several tools appear, and some have actually been preliminary tried, suited for that task, such as temporal and spectral analysis, or even machine learning techniques.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a system that is able to measure the GRFs, in real-time, of a walking humanoid robot. The ITshoe is a cost-effective, self-contained and low-power battery-powered device that does not affect the balance of the robot. The ITshoe design simplifies its use with a variety of humanoid robots, since it only requires a change in its coupling geometry, that can be extracted from the robot foot in question. Nevertheless, more research, refinements and extensions are desired to improve its functionality and accuracy.

Using computational techniques models, either in spectral analysis or machine learning, in the near future, it is expected to be possible to distinguish different floors by analysing the patterns, obtained by the force sensors, for different grounds. Additionally, it is also expected that this data can be used for several other studies within this theme, to improve the performance and balance of biped humanoid robots.

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