DESIGN OF A MULTIFUNCTION FOOT MANIKIN FOR FOOTWEAR TESTING

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Abstract. *Locomotion is a fundamental aspect of human activity. If for the great majority of people, it may be viewed in a perspective of pure comfort during long periods of low intensity activity (light work, strolling), for other sectors of the population, the priorities are quite different. In one extreme, one may consider the prime objective to help the handicapped, those with disfunctionalities in the lower members. At the other end, one may consider those engaged in high intensity activities (for example, running) where performance (in terms of efficiency in converting the body energy into useful work) is the main concern. Whatever the purpose and the perspective, the interaction between the foot and the shoe is of the utmost relevance. The main objective of any footwear is to provide adequate levels of comfort during use. Comfort depends upon a variety of parameters such as temperature, humidity through sweating and contact pressure distribution. It is known that the surface temperature varies along the foot. Although it represents a small part of the body, the comfort perception by an individual is strongly affected by the foot temperature, particularly if there are strong temperature gradients within the body. Sweat is also in an important factor in thermal regulation. Therefore, the ability of any footwear to efficiently remove the body moisture is of great relevance. This is related with the selection of fabrics for the inner linings and the shoe materials. This paper reports the design and development of an artificial multifunction foot to duplicate and test in laboratory, among other applications, a human foot with the purpose to test and evaluate the performance of footwear under certain conditions (such as walk and run), for a standard foot size of 41-42. This robot-foot should be hinged, with 2-3 degrees of freedom, enabling fingers flexibility and rotation of the ankle, being also capable of simulating the superficial temperature as well as the sweating of a human foot inside a shoe. This artificial foot mechanism should also enable the slippage of the artificial foot inside the shoe, as well as the sole-soil slippage for measuring the friction. This paper will briefly discuss and analyse the mechanical design carried out in terms of conceptual design, and will detail the selection of the necessary sensors and actuators and its implementation on the prototype. The overall instrumentation and control system architecture will also be presented and discussed throughout the paper. This research effort represents a major step towards the future goal that we intend to accomplish within our R&D center for the reseach on motion and gait analysis, as well as for testing footwear performance and confort.*

Keywords*: Biomechanics, Mechatronics design, Artificial foot manikin, Locomotion, Footwear performance*

1. INTRODUCTION

In an attempt to avoid the limited procedures used and the disadvantages of the testing methodologies existing for the whole shoe, the design, construction and implementation of an adequate apparatus suitable for footwear testing is the main objective of the authors, in direction to an even more objective evaluation of footwear and its materials and/or components.

This apparatus is focused on the use of an artificial foot manikin capable of simulating, in laboratory, the "normal" human foot conditions to test and evaluate, under certain conditions, the performance of footwear. This apparatus suggests the use of an articulated physical model, similar to a human foot, regarding its anatomic and anthropometric aspects. This artificial foot will be coupled to a mechanism capable of simulating the human gait cycle (already designed for this purpose), and will also include a superficial temperature and sweating system. The overall apparatus will have the ability to test several parameters simultaneous, such as thermal comfort and footwear durability…

The multifunction feature addressed to this apparatus can be also important for other applications. One of these applications is concerned with the rehabilitation procedures of human lower limbs: this apparatus can be used as a rehabilitation device maintaining the limb in a functional position (using a full malleable adjustable frame) while it continues to workout the affected limb.

Before developing the artificial foot, a state of the art research regarding footwear testing systems and equipments was carried out.

According to this research it is possible to identify several foot manikins capable of simulating the human sweating and thermal behaviour, as well as gait cycles in order to assess footwear performance.

The Thermal Foot Test System (or TFTS) of the Measurement Technology Northwest (USA) (MTNW, 2008), the Advanced Moisture Management Test (AMMTest) of the SATRA Technology Centre in the UK (SATRA, 2008) and the Whole Shoe Comfort Rating Method (WSCR method) of the TNO Industrial Technology in the Netherlands (Schols *et al*, 2004. are just three examples of static foot manikins for simulating superficial temperature and sudation.

In terms of dynamic foot manikins, the Biomechanical Abrasion Machine (SATRA Technology Centre) (SATRA, 2008) and the Thermal Foot Manikin System (Jožef Stefan Institute, in Slovenia) (Mekjavic *et al*, 2003 and Mekjavic *et al*, 2006) are two proposed solutions: the first one is used to carry out biomechanical abrasion tests and the second one to test the durability and the biomechanical properties of footwear. The latter system also comprises a heated thermal foot manikin with a sweating function, making it possible to evaluate thermal comfort of footwear in static and dynamic conditions.

The apparatus designed by the research team gathered in this project also uses a four-bar based mechanism, as a gait simulator, allowing a good reproduction of the human gait cycle in terms of simulating the real trajectory of the ankle during the stance phase. This development has already been published elsewhere (Machado, 2007 and Machado *et al*, 2007) as part of the research work being undertaken at the University of Minho in this domain. The following topics will present the overall design architecture as well as some of the purposes of this development.

2. THE ARTIFICIAL FOOT CONCEPT

For this particular project, a representation scheme framework was drawn as depicted in figure 1. The overall project comprises the development of an hinged foot, sudation and temperature systems.

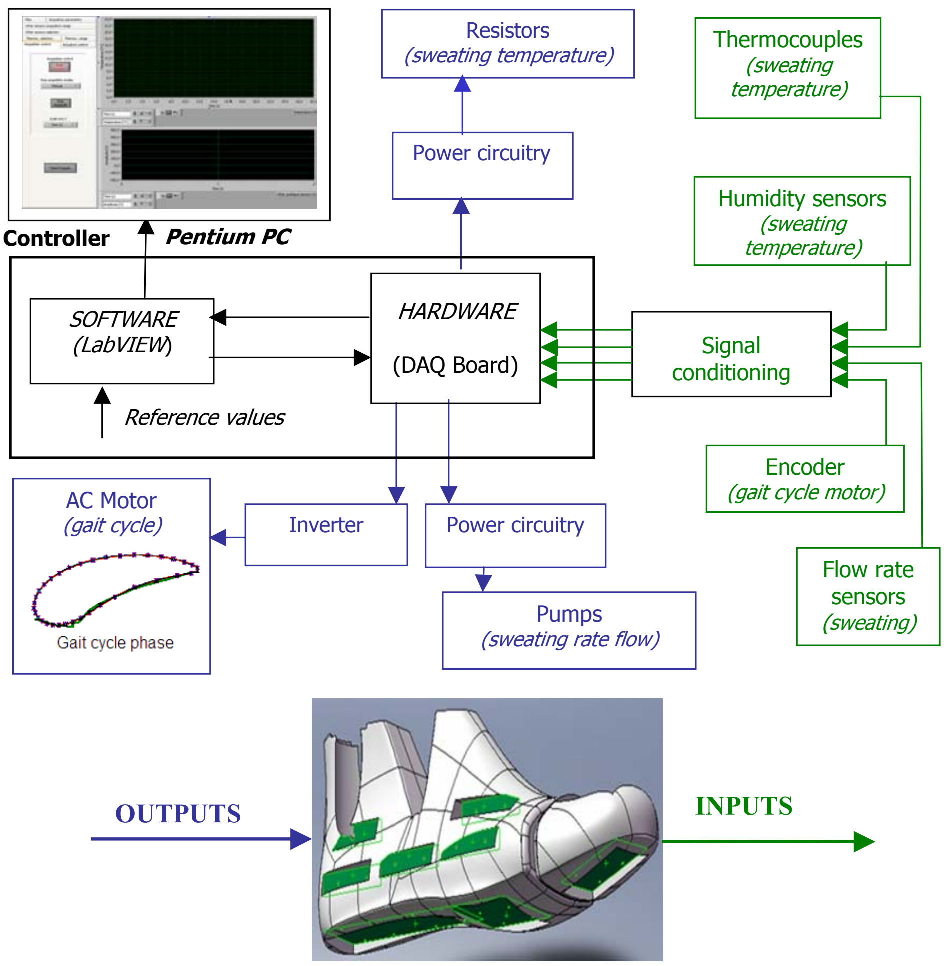


Figure 1. Project framework to be implemented.

The artificial foot will be instrumented with temperature and humidity sensors for the sweating phase, and position and speed sensors for the gait cycle phase.

Several signals will be addressed to a PC-based controller, which includes a data acquisition board. A specially designed software tool in LabVIEW (from National Instruments) will be used to ease acquisition, visualization and analysis of the obtained signals, as well as to enable the command and control of the overall (temperature, humidity and gait cycle) system.

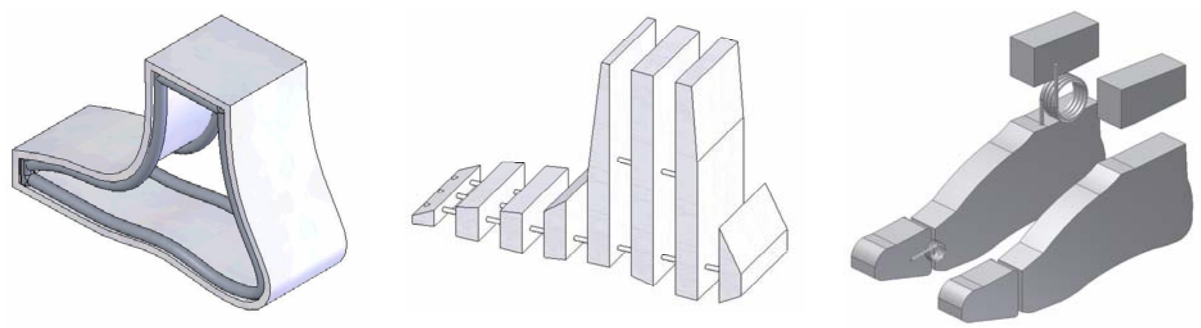
Considering just the sweating phase, the controller will compare the sensor readings with the ones tabled on a database: these values indicate the real temperature and sweating rate of a human foot (as reference values) when affected by a gait speed over a certain period of time. If the measured values will be different from the ones listed as the reference values, the controller will actuate, through the power circuitry, the pump or the resistors in order to increase, or decrease, the temperature and/or the sweating foot rate. This will be constantly monitored and controlled, since at least one of the control variables will be always changing: the gait time.

It must also be emphasised that other research work, involving the same staff of this research team, is currently running to determine (among other issues) the needed reference values for the sweating phase, which also gathers a Portuguese technological centre as industry partner.

2.1. The hinged foot system

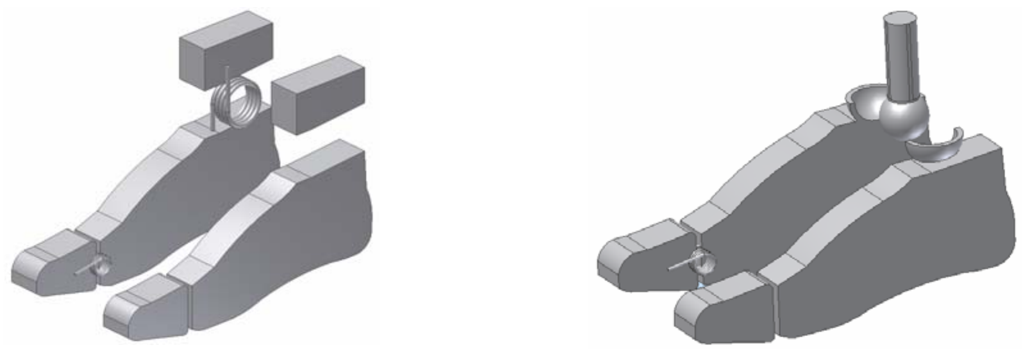
The foot needs two hinged joints: one near the fingers (metatarsus) and the other near the ankle. Different conceptual solutions have been achieved to accomplish this objective. Figure 2 depicts three possible solutions. For the model presented in figure 2-c), two different suggestions have also been considered: these alternatives only differ on the replacement of one spring (in the ankle) by a spherical joint – see figures 3-a) and b).

After considering the importance of all the different parameters involved, the adopted solution was the one presented in figure 3a). The foot is therefore made up by three parts: one central part and two lateral parts.



a) b) c)

Figure 2. a) b) c) Three conceptual solutions considered for the hinged foot.



a) b)

Figure 3. a) b) Two alternatives for the proposed solution of figure 2-c).

The central part is symmetrical and in this part the spring components will be attached, two in each spot (side by side), near the fingers and near the ankle. This central part will also accommodate the perspiration channels and the tubes for the sweating phase, as well as for the wiring of the sensors and resistors – see figure 4. To avoid strangling the electrical wires and tubes during the bending of the foot system, they will also pass through the central part and the two lateral parts. It must also be noticed that once the springs, wires and tubes are fixed, both lateral parts will be assembled together in order to improve the stiffness of the foot and to provide the volume and shape needed for the footwear testing – see again figure 4.

The springs perform an important role to enable an hinged arrangement, providing a return of the foot to an initial position during the progress of the gait cycle. Although the previous figures do not show in detail this mechanical component, torsion springs with linear wires on both ends were selected for this application.

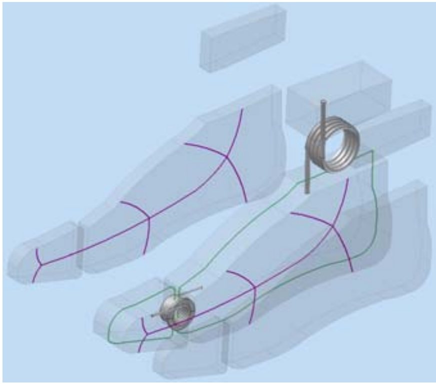


Figure 4. Sudation phase and sensors wiring.

These springs will accommodate the torsion forces present although it is also expected them to hold the foot in place and to bring it back to its initial position during the planar flexion and dorsiflexion actions, that occur in the gait cycle.

To enable an adequate flexion and dorsiflexion actions of the articulated joints (fingers and ankle), it was also necessary to round the ends of each of the connected parts of the foot. To avoid some of the wear resulting between the slippage of the spring on its housing, nylon bushings were also used. Figure 5 highlights this arrangement near the fingers zone. A similar arrangement was also designed for the spring attachment in the ankle zone.

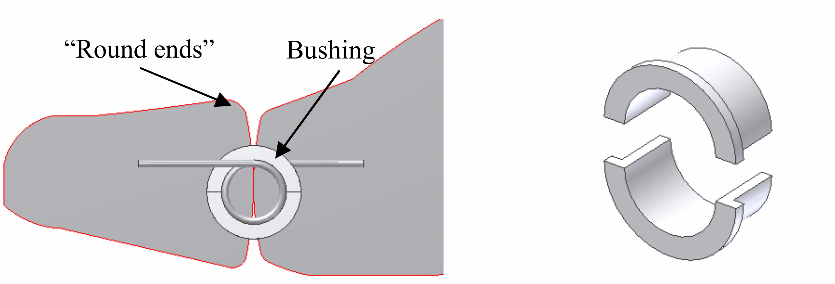


Figure 5. Spring attachment (left) and nylon bushing (right).

2.2. The sudation system

This system will simulate the human sweating of a real foot when inside a shoe.

The apparatus set-up needs a pump to guarantee a very small sweating flow in the foot. The standard sweating rate of a normal human is approximately 0,46 ml/min (Shamsuddin *et al*, 2005). Due to the reason that the sweating rates depend on the foot temperature, the selected pump must have an analogue input to enable a flow change. Peristaltic pumps guarantee these operating conditions: therefore the CASED - IP66 EASY TUBE LOAD (as presented in figure 6a) was selected for this application.

This pump has different control types (manual, analogical or digital) and is capable to operate liquids of different viscosities and densities, important to test different solutions that could be similar to the human perspiration.

For obvious space reasons, the pump will have to be placed outside the artificial foot. To supply an aqueous solution to the foot, small conducts in flexible and transparent PVC tube will be used. This tube type is available with diameters between 1,6 mm and 4 mm (see figure 6b) and could support temperatures up to 65 ºC. These tubes will be placed through the cylindrical holes manufactured in the central part of the hinged foot system.

To achieve a better perspiration distribution in the foot surface, some cavities (the green zones presented in figure 7) will be manufactured in the end of the tubes, which will be filled with a porous material and covered with resistors, to spread and simulate, into a larger area, the human perspiration. These rectangular cavities are located three in the bottom of the foot and five in each lateral part – see again figure 7.

a) b)

Figure 6. a) b) Peristaltic pump and PVC tubes selected (VERDER, 2008).

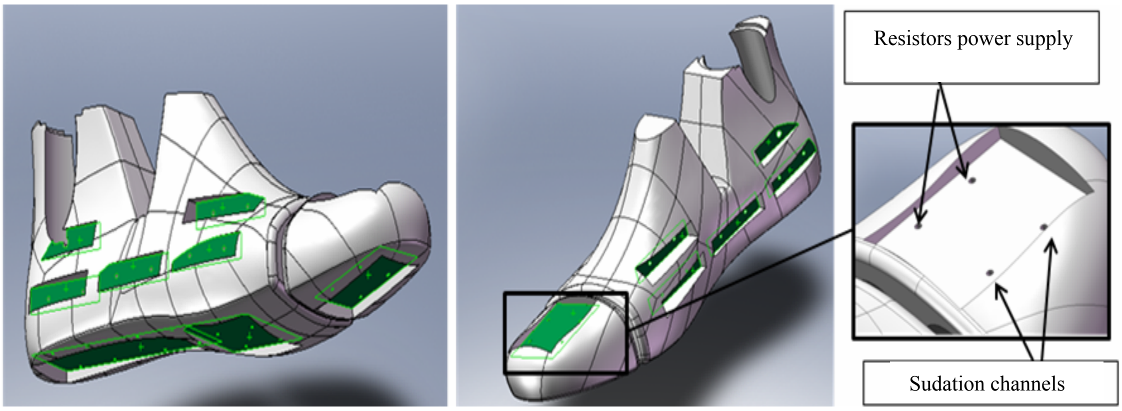


Figure 7. Cavities location and channels identification on the designed foot manikin.

Several materials were considered for this purpose. A cotton mixture with polyester was selected, because it presents good capacity to absorb and release humidity and has good durability.

To measure the humidity in the foot, small humidity sensors (HIH-3610 (HONEYWELL, 2008)) were selected, since they only need a contact area of 4,27 × 9,47 mm^2. These sensors can operate under temperatures up to 85 ºC and they also have a polymeric layer that protects them against dust and dirt.

Figure 8 shows the assembly of the sudation system implemented in each of the 14 cavities considered on the developed foot manikin.

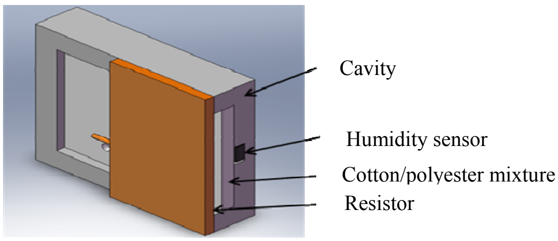


Figure 8. Sudation system assembly.

2.3. The temperature system

As mentioned in the previous section, in the foot surface there are some cavities (see again figure 6) where the electrical resistors will also be attached. These resistors will be responsible for simulating the superficial temperature in the foot.

In average terms, the superficial temperature of the foot is approximately 34 ºC (Mekjavic *et al*, 2003), oscillating around this value depending on the dynamic activity of the foot. Due to these oscillations, a relatively wide temperature operation interval was defined, ranging between 30 to 50 ºC. Another important parameter is the fact that these resistors are present in a humid operation environment due to the implemented sweating system.

The available resistors that better adapt to this purpose are the flexible resistors. This resistor type can be easily adapted to the foot shape and they have a silicon membrane making them impermeable; these resistors are available in small dimensions – see figure 9.

Each cavity in the foot will have a resistor of 70 W to guarantee the required interval of temperatures.

Figure 9. The adopted resistor (KATCO, 2008).

The temperature is monitored by E-type (Cromel/Constantan) thermocouples located in the vicinity of the resistors. This temperature sensor type can be used in humid environments without losing its measurement efficiency. It has a measurement range that is quite adequate for this testing apparatus.

Figure 10 shows, as an example, the implemented closed-loop control architecture for the temperature system that simulates the superficial temperature in the foot: the superficial temperature measured by an E-type thermocouple is addressed to the controller by an analog-to-digital converter (ADC); the digital data is then processed by the controller using control equations; finally the resulting data is converted by a digital-to-analog converter (DAC) to supply an output correction to the resistor.

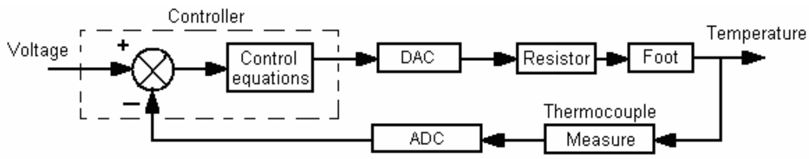


Figure 10. Representation of the implemented closed-loop control for the superficial temperature in the foot.

A similar control scheme is to be implemented for the peristaltic pump, in order to control the sweating flow rate.

2.4. Materials

The material selection was accomplished based on mechanical, chemical and thermal factors. Another important factor was the overall costs: a cost-effective solution should be designed. At the mechanical level, a rigid and robust frame in order to resist and support the operating loads, as well as to enable a fast coupling of all components, was an important issue to have in mind. The selected materials should also provide chemical protection, due to the corrosive action of the "perspiration" solution. High thermal resistance is needed due to the high temperatures reached inside the footwear. A material easy to manufacture (to minimize preparation costs), as well as the overall apparatus cost and dimensions were also important design requirements. According to all these factors, it was concluded that polyamide would be a good solution for the artificial foot.

3. DATA ACQUISITION SYSTEM

The data acquisition system is made up by several modules, provided by National Instruments, and arranged as shown in the figure 11. A terminal block module (SCXI-1303) will be used to connect the temperature and humidity sensors. For compensating cold junction, this module includes a thermistor to measure the temperature in the thermocouples connections. On the other hand, this terminal block will be connected to another module (SCXI-1102) for conditioning the acquired signals. This conditioning module will be linked to a chassis (SCXI-1100), to power their circuits and modules, and to allow the expansion of the acquisition system, if necessary. This chassis will be connected, through a 68 pin cable, to a data acquisition board (PCI-6251DAQ board) installed in a PCI bus of a desktop computer (PC). Finally, it will be used the LabView software (or Laboratory Virtual Instrument Engineering Workbench, again from National Instruments) to carry out the acquisition, visualization and analysis of the data and to perform the command and control of the overall system.

LabView is a graphically-based programming language developed, as mentioned, by National Instruments. Its graphical nature makes it ideal for test and measurement (T&M), automation, instrument control, data acquisition and data analysis applications, resulting in significant productivity improvements over conventional programming languages (Bitter *et al*, 2001).

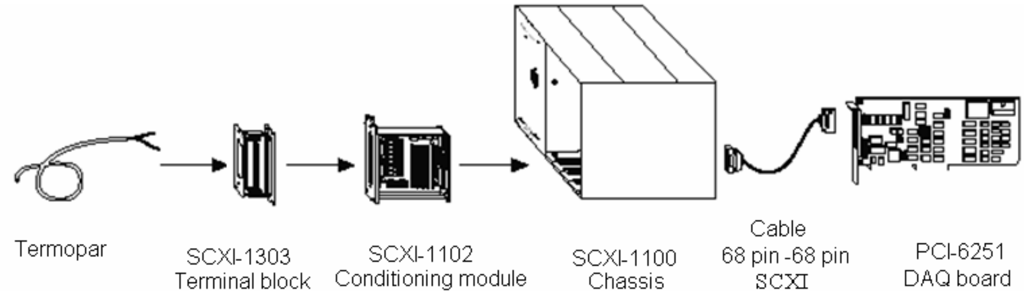


Figure 11. Architecture of the adopted data acquisition system hardware.

LabView is a program development environment, much like modern C or BASIC development environments, and National Instruments LabWindows/CVI. However, LabView is different from those applications in one important aspect: while other programming systems use text-based languages to create lines of code, LabView uses a graphical programming language to create programs in a block diagram form (Bitter *et al*, 2001).

LabView, like C or BASIC, is a general-purpose programming system with extensive libraries of functions for any programming task. This software allows a high configuration flexibility, to perform data acquisition, data analysis, data presentation and data storage.

Due to these advantages, a LabView application was developed to enable signal acquisition from the thermocouples, humidity sensors, motor incremental encoder and flow rate sensors (as system inputs), as well as to carry out data analysis and to provide the needed actuation (based on control equations) of the resistors, the peristaltic pump and the motor for the gait cycle (system outputs).

On the other hand, to obtain the displacement and foot velocity during the gait cycle, a high speed camera from Photron was selected (PHOTRON, 2008). The acquisition, treatment and analysis of the obtained gait cycle images will be carried out using specific hardware and software available from the camera manufacturer.

Table 1 depicts the inputs and the outputs used (with the respective control mode) for the developed acquisition and actuation system.

Table 1. Inputs and outputs for the acquisition and actuation system.

INPUT	OUTPUTS	OUTPUT control mode
32 Thermocouples (to obtain the “foot” temperature gradient)	14 Resistors (one for each cavity - see figure 7)	ON/OFF (digital) – as a function of the temperature and humidity
14 Humidity sensors (one for each cavity - see figure 7)	14 Peristaltic pumps with variable flow	Continuous (analogue) – as a function of the temperature and humidity
1 incremental encoder (to measure the rotation speed of the gait cycle motor)	1 Motor AC with variable speed (for gait cycle rate)	Continuous (analogue) – as a function of the gait cycle rate
14 Flow water rate sensors (one for each cavity - see figure 7)		
1 high speed camera (to obtain the displacement and velocity of the foot manikin)		

Figure 12 shows the main panel of the so far developed LabView software. On the left hand side of this panel there are different menus where all the considered parameters for data acquisition, analysis, presentation and storage, and actuation control can be selected. In this particular case the data acquisition menu can be seen. On the right hand side of this figure there are two charts: the one on top is for the display of the thermocouples signals while the other on the bottom side is used to display the humidity, encoder and flow rate signals.

Figure 13 shows some software menus related with the configuration of the system inputs.

On the other hand, figure 14 shows another software menu, associated with the outputs for the control system.

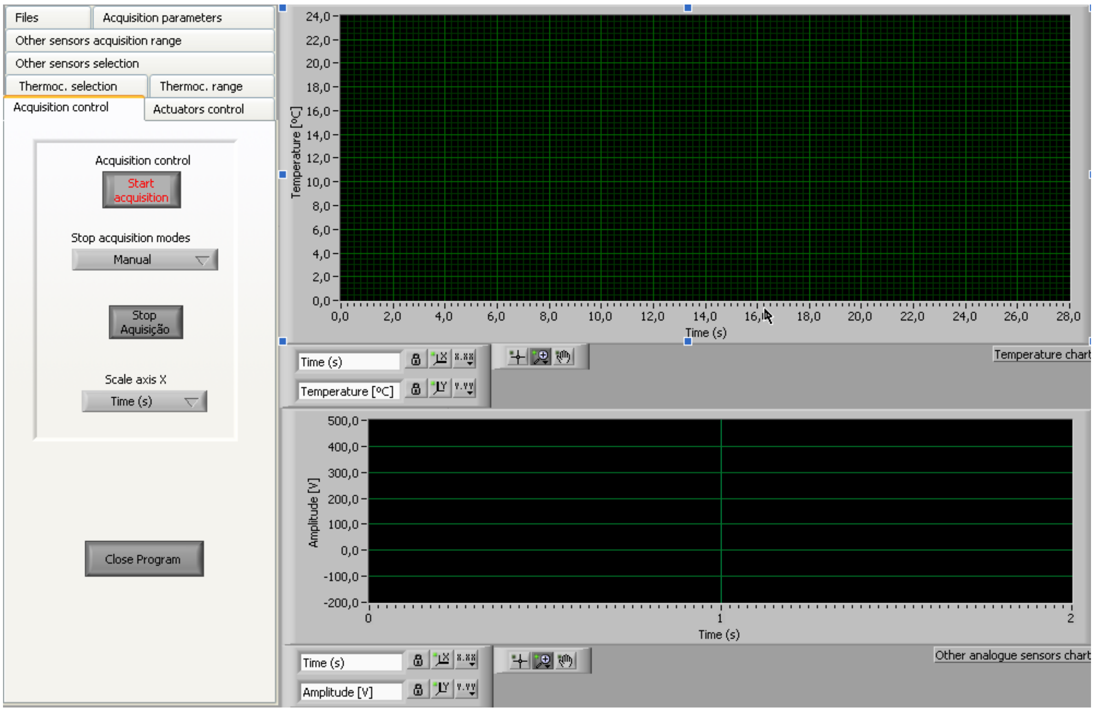


Figure 12. Main panel of the developed software.

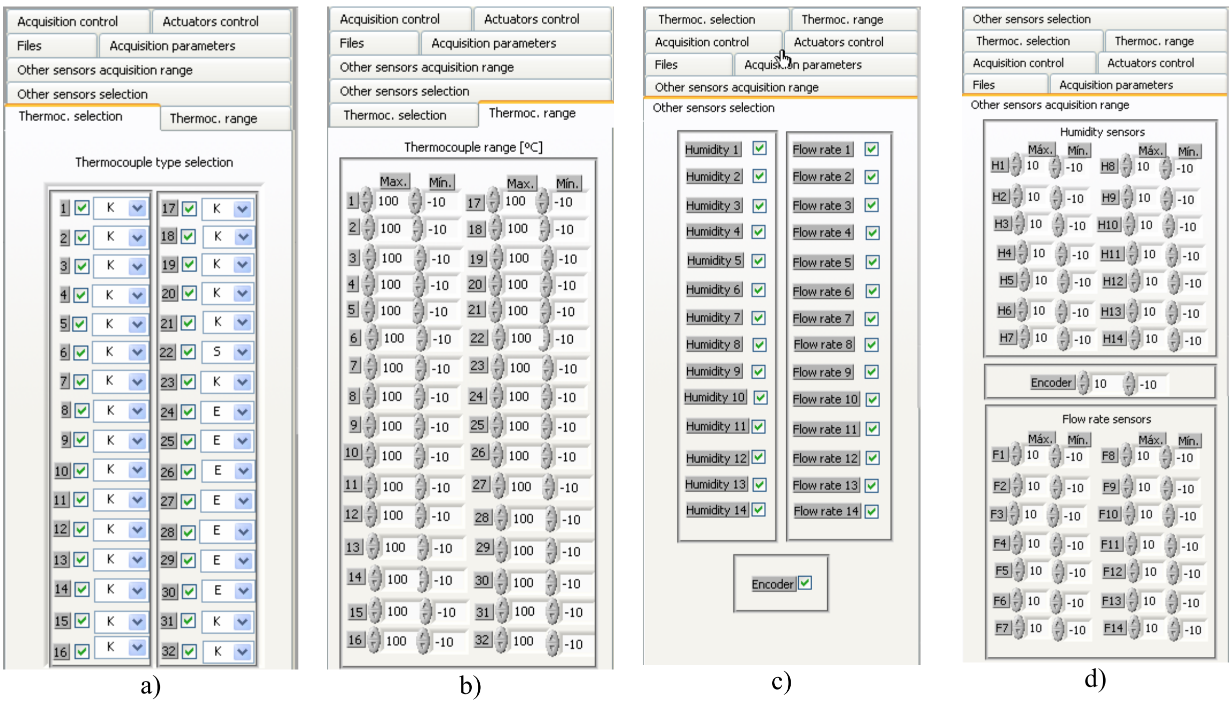


Figure 13. a) b) Thermocouple type selection and range; c) d) Other sensors selection and range.

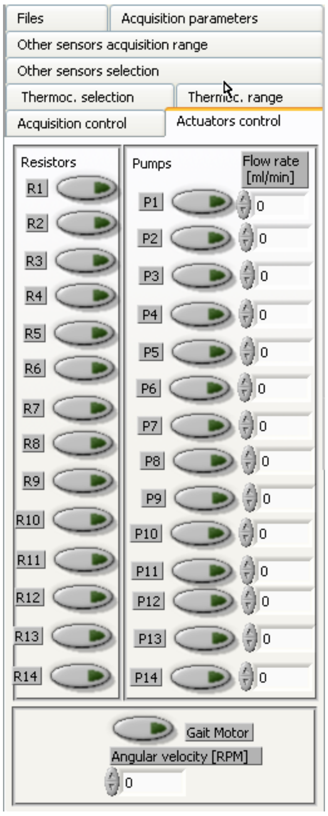


Figure 14. Actuators control menu (ON/OFF control for the resistors and analogical control for the pumps and gait cycle motor).

4. CONCLUSIONS

In order to perform comparative tests and analysis of different footwear models, components and materials, an apparatus for footwear testing was designed and developed, to obtain a more objective and reliable evaluation that should be independent of personal subjective interpretations. This system should also be capable to automatically control the parameters involved in the locomotion, such as speed, acceleration, sweating rate and superficial temperature.

Although there are several other applications in the market, the herein proposed design is also innovative, since it will incorporate a gait cycle simulating frame, capable to perform the real trajectory of the ankle during the stance phase. As mentioned, this apparatus can also be used as a rehabilitation device, which has captured a special interest from, at least, to main sectors: the shoe industry and the rehabilitation instruments industry.

This paper highlighted the design phase carried out so far, and future work will be focused on the detail design and analysis regarding the hinged foot, sudation and temperature systems, as well as on the implementation of the overall (electronics hardware and software) systems architecture to monitor and control the testing apparatus. On a second stage, the upgrade of the apparatus will also be considered, which will include a pressure platform to measure foot pressures and contact zones; this procedure will be helpful to compute the wear of the footwear sole and to validate the gait cycle approach used in this study.

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6. RESPONSIBILITY NOTICE

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