A Distributed Pressure Sensor to Measure Human-Machine Interaction in Lower-Limb Exoskeletons

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***Abstract*—We present two generations of distributed pressure sensors used in human-machines interfaces of lower limb exoskeletons. These sensors are based on a mechano-opto-electronic transduction principle. The first generation was tested with LOPES exoskeleton, the second one, a digital system with an higher resolution, was preliminary tested with the LOKOMAT® exoskeleton. The results show that these sensors can be used to monitor the human-robot interaction in a lower limb exoskeleton during gait tasks.**

***Keywords*—Distributed pressure sensors, physical human-robot interaction, lower-limb exoskeleton, sensorized cuff.**

I. INTRODUCTION

The most widespread way to connect wearable robots with the user's limbs are connection cuffs and orthoses. Connection cuffs are soft belts of adjustable size that are fastened to the user's limbs: one cuff is used for each connection point. An example of this solution is adopted in the LOKOMAT® exoskeleton [1] and in the LOPES lower-limb exoskeleton [2]. Orthoses are shells made of plastic or other orthopedic materials which can be worn on the part of the limb onto which the rehabilitation robots apply forces. A pressure measure of the physical interaction between the robot and the user's limbs is of critical importance to understand how the exoskeleton is interacting with human. Two different prototypes of distributed pressure sensors to measure interaction forces in lower-limb exoskeleton using connection cuff, were developed and are presented in this work.

II. WIRED PRESSURE ARRAY – GENERATION I

A. Sensor design

The sensor is composed of an array of sensitive elements based on a mechano-opto-electronic transduction principle. This sensor is made of two main components: a flexible printed circuit board (PCB), which houses the sensitive elements, and a soft silicon shell [3]. Each sensitive element is composed of a light emitter and of a light receiver, and the whole sensor is covered by a soft silicone shell. The PCB, with a thickness of 0.2mm, houses a light emitter (an InGaN chip technology, high luminosity green LED) emitting light along the longitudinal direction, and a photodiode (an analog ambient light opto-electronic transducer with current output), which gets the light from the side. The shell is directly involved in the transduction principle and provides structural functionality at the same time. When a load is applied on the sensor, it deforms its structure, which occludes the light path from the transmitter to the receiver, and reduces the light which reaches the photodiode, changing its current output. The material we used was a shore A 40 platinum-catalyzed silicone (Sorta Clear 40, Smooth-On, Inc., Easton, PA, USA), colored with a black pigment.

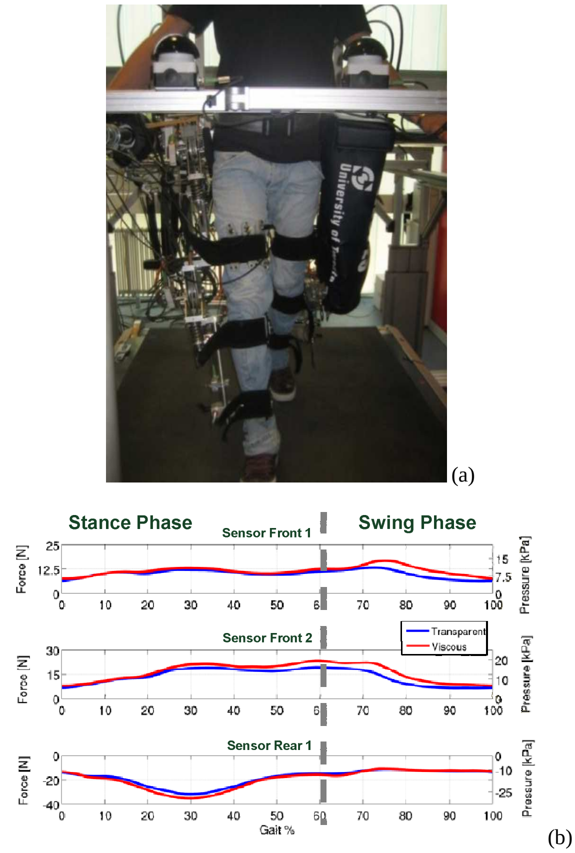

Figure 1. (a) First generation of sensors during a walking task with LOPES exoskeleton (Figure taken from [3]); (b) Force and pressure distribution on three sensors during a walking task.

Each sensitive element has a dynamic, non-amplified range of about 0.2V, with an output impedance of 22kΩ. The signals are acquired using a 32-channels ADC board, with a sampling frequency of 2kHz, and digitally filtered with a fourth-order Butterworth filter with a cutoff frequency of 40Hz. The acquisition and filtering routines were implemented using National Intruments^{TM} Labview® 2009. The dimension of the sensor was chosen specifically for this application: length of 60mm, width of 20mm and thickness of 8mm. An interaction force range requirement of 60N, corresponding to an average pressure on the pad of 50kPa, was chosen based on a series of preliminary experiments. To infer the exact pressure acting on each pad from the eight voltage output, the sensor needs to be characterized in its structural and electrical behavior. Both characterizations were obtained by applying a load on the sensor using a rigid flat body, while recording sensor deformation and voltage. The characterization was performed using an INSTRON 4464 testing machine (INSTRON Inc., Norwood, Massachusetts, USA), equipped with a 1kN load cell. Five loading-unloading cycles were performed at a speed of 0.1mm/min for each pad to give its quasi-static characterization.

Figure 2. (a) Representation of the transduction principle of the second generation (Figure taken from [4]); (b) Second generation of sensors with LOKOMAT® exoskeleton.

B. *Results*

We present an analysis of the interaction pressure distribution during a gait training task with the exoskeleton LOPES. In this experiment, a subject linked to the exoskeleton through three attachment points for each leg (thigh, shank, ankle), was asked to walk on a treadmill at a constant speed of 4km/h for about 250 gait cycles. The trial was carried out in two different conditions: the exoskeleton was controlled in zero-torque mode, to operate as transparent as possible; using a viscous field of $10Nm/rad\cdot s^{-1}$ applied at the hip joint, to simulate a gait training task. The thigh connection was sensorized with six sensitive elements, three in the front and three in the back, put between the flexible belt and the user's limb. Figure 1 (b) reports the results of acquisition on three parts of the thigh cuff: the x-axis represents the percentage of the gait cycle, y-axis reports how pressure distribution varies during the gait cycle. The beginning of the cycle (0–100%) corresponds to the foot impact on the ground. The stance phase ranges from 0 to about 50–60% of the cycle, where the toe-off takes place. The remaining part of the cycle (60–100%) corresponds to the leg swing phase.

III. WIRELESS PRESSURE ARRAY - GENERATION II

A. *Sensor design*

The second generation is composed of two main parts: the sensitive part and the electronics board. The sensitive part is assembled on a flexible PCB with a thickness of 0.2mm (the technology was first presented in [4], and a patent is currently pending [5]). Each sensitive element is composed of a light emitter and a light receiver, and the sensor is covered by a silicone shell. The sensor has a pyramidal shape, with a base of about $1cm^2$ and an height of 5.5mm. When the load is applied on the sensor, the silicon is subject to a deformation and obstructs the light path from the LED to the photodiode, changing its voltage output (Figure 2 (a)). The interaction force range of each sensor is of 15N, corresponding to a maximum pressure on the sensor of 150kPa. Each sensitive element has a dynamic, non-amplified range of about 1V. Two versions were realized: a prototype composed of an array of 16 elements (4x4), and a second prototype of 32 elements (4x8). The 4x4 system was used to sensorize cuffs of ankle and shank; instead the 4x8 system was used to sensorize the cuff of thigh (Figure 2 (b)). The power consumption of the device is about 50mA at 3.6V for the array 4x8, and the half for the system 4x4. After production each system was characterized in its structural and electrical behavior using a three-axial robotic platform able to provide controlled loads or deformations to any given position.

B. *Electronics Board*

The array of sensors is connected by a flat cable to an external electronic board to signal acquisition and elaboration. The board comprises analog digital converters and a microcontroller to perform signal processing. The board is connected to a Bluetooth receiver/transmitter (RoboTech s.r.l., Pisa, Italy) on a UART socket. The board is powered by a battery which can power the unit for up 7 hours in continuous working mode. The board can acquire 64 signals at 1.8kHz frequency through four 16-channels 14-bit ADCs. Signals are low-pass filtered and de-sampled to 100Hz. Each digitalized voltage is used to determine the pressure on the corresponding sensitive element through a third-order polynomial function.

IV. CONCLUSION

In this work two generation of prototypes of distributed pressure sensors to measure human-machine interaction in lower-limb exoskeleton using connection cuffs were presented. The first generation is a wired system, cabled and analog; the second one is wireless, digital, plug-and-play and has an higher resolution. The first prototype was tested with the LOPES exoskeleton. Results of gait tasks show that our sensors can be used to monitor human-robot interaction in a lower limb exoskeleton. The second prototype was preliminary tested with the LOKOMAT® exoskeleton.

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