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TRIBOLOGICAL CHARACTERIZATION OF THE CONTACT SURFACE OF SENSORS USED IN THE STRUCTURE OF EXOSKELETONS

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Abstract - Medical rehabilitation systems, such as exoskeletons have become an important solution for restoring mobility in patients affected by spinal cord injuries, stroke, and muscular atrophy. These systems are designed to support or even assume the locomotor function of individuals with impaired mobility, enabling them to perform daily activities more easily during the rehabilitation process. Their functionality relies on the integration of mechanical components, sensors, and actuators, with sensors playing a crucial role in detecting the user's movement intentions and transmitting signals to the actuators, which subsequently generate the motion of the exoskeleton components. The typology, integration, placement of sensors within the exoskeleton structure, and the system's material significantly influence the durability and operational reliability of the system. During prolonged use, sensors are exposed to mechanical wear, which may reduce their performance and negatively affect the lifespan of the rehabilitation device. To address this issue and improve wear resistance, force sensors were coated with biocompatible materials layers possessing enhanced tribological properties. Polyethylene (PE) and ethylene-vinyl acetate (EVA) layers of different thicknesses were evaluated through technical-functional, physical-mechanical, and tribological analyses. The obtained results demonstrated that protective coatings effectively reduce sensors surfaces wear. From the tested materials, the 1.5 mm EVA coating layer provided the highest level of protection, indicating its suitability for extending the operational lifespan and reliability of sensor-integrated exoskeleton systems.

Keywords: Sensor, Exoskeleton, Wear, Roughness, Ethylene vinyl acetate, Polyethylene, Tribological characterization.

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1. Introduction

1.1 Rehabilitation Systems – Exoskeleton

Rehabilitation systems are assistive devices designed to support patients who have partially or completely lost their physical abilities following accidents, neurological disorders, or degenerative conditions (e.g. activities performed in improper postures). [1] Mobility impairments are commonly encountered in individuals affected by brain tumours, strokes caused by ischemia or aneurysms, traumatic brain injuries, spinal cord injuries, limb amputations, while elderly individuals are also frequently affected due to muscle atrophy and age-related decline. [2]

Medical studies show that mobility impairments affect a big number of people worldwide, highlighting the increasing demand for advanced rehabilitation systems. The growing importance of rehabilitation technologies is reflected in their essential role in improving patients' quality of life and functional independence.

Among these technologies, exoskeleton-type rehabilitation systems are electromechanical devices developed to restore or enhance impaired motor functions caused by different disorders. Depending on their design, they can be mobile, wearable on the affected segment of the body, or fixed, providing support for patients in performing daily activities such as walking, standing, lifting, and objects' manipulation. By enabling immobilized people to perform daily activities more effectively, exoskeletons help restore functional independence, providing a more active and autonomous lifestyle.

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[3], [4]

Thus, there are passive and active exoskeletons to provide patients stability and to help them with the movements' realization, respectively. Passive exoskeletons operate using the wearer's own muscular force, whereas active exoskeletons rely on external power sources such as batteries, pneumatic systems, or hydraulic energy. Passive systems function by storing part of the user's kinetic energy as mechanical energy and subsequently convert and release it into kinetic energy to assist the patient's movement. The absence of external power supplies makes the passive exoskeletons lighter, more flexible, and generally easier to use. [5]

An exoskeleton designed for rehabilitation of locomotion is a complex mechatronic system that contains interconnected rigid components, like detection and actuating components, command and control unit, electrical power supply system and human-machine interface. [6] The detection components, represented by sensors, are used to identify and capture changes in the body's electrical signals generated when the patient intends to move. These signals provide information regarding the functional state of the exoskeleton and trigger the actuating components — the actuators — which generate the mechanical force necessary to facilitate the patient's movement. Through this interaction, the sensors continuously monitor the user's movement intentions and activate the mechanical elements of the exoskeleton in real time. For instance, in lower-limb exoskeletons, pressure sensors may be employed to detect the forces applied on the legs, while electromyographic sensors detect the electrical activity generated by muscle contractions. The information collected by these sensors is processed to control the actuators — such as electric motors, hydraulic systems or pneumatic mechanisms — which generate the movements required to assist the patient in activities like walking, maintaining stability or leg lifting. [7] The command and control unit coordinates the information flow between sensors, actuators, and motor controllers, while the electrical power supply system ensures the energy required for operation. Through the human-machine interface, users can transmit commands and receive real-time feedback, enabling efficient and adaptive rehabilitation assistance.

Exoskeletons are manufactured from various biocompatible materials that have a high degree of strength and durability, such as polypropylene, carbon fibre, or metallic alloys, chosen according to the specific purpose and functional requirements of the device. While certain exoskeletons rely on rigid structural components to ensure stability and mechanical support, others incorporate softer and more elastic materials to improve flexibility and user's comfort. Despite their important role in enhancing mobility and rehabilitation, these systems may become relatively heavy and inflexible, particularly when worn for prolonged periods. Consequently, the materials used in their construction must achieve a balance between rigidity, lightweight design, and comfort, supporting patients in performing movements more easily and naturally. At the same time, the rigid structural elements can create discomfort when are applied directly to the skin, leading to its damage due to the prolonged friction or pressure.

1.2 Sensors Integrated in the Structure of Exoskeletons

Sensors are the fundamental component of exoskeletons, because they detect the user's movement intentions and variations in physiological signals, predict joint loading, and trigger the actuators of the rehabilitation system accordingly. Thus, the real-time data collected by the sensors control the activation, intensity, and ending of the assistance delivered enabling the system to supply the appropriate amount of power to each joint precisely, when is necessary. As a result, the exoskeleton effectively assumes the locomotor function of individuals who are unable to move independently.

In the exoskeletons structure, there can be used three main types of sensors: sensors that estimate the internal state (e.g. force sensors, joints position encoders, and inertial measurement units); sensors that monitor the exoskeleton's interaction with its surrounding environment (e.g. proximity sensors and sensorized insoles); and sensors that directly assess the user's physiological and neuromuscular condition (e.g. electromyography, heart rate, and electroencephalography sensors). [8]

Sensors from the first category mainly facilitate the kinematic and dynamic regulation of the exoskeleton joints according to the required level of assistance, while those from the second and third categories are mainly employed to identify the user's movement intention. [9].

A lower limb exoskeleton incorporates a wide range of sensors to measure force, position, and motion, enabling accurate acquisition of data regarding the orientation, location, and velocity of each component. This is essential for the effective control and coordination of the exoskeleton.

Depending on the physical parameter being measured, exoskeleton systems integrate various types of sensors to monitor user's movement, interaction forces, and system conditions. Position [10] and inertial [9] sensors are used to assess joint angles, orientation, balance, and gait dynamics, enabling accurate and adaptive motion control. Force [11] and pressure [12] sensors measure interaction forces, mechanical loads, weight distribution, and gait phases, contributing to user intention detection, real-time feedback, and safe interaction between the human and the system. In addition, biosignal sensors [13] monitor muscle activity and neuromuscular conditions to improve control responsiveness and replicate natural movement patterns, while temperature sensors [14] supervise thermal variations to prevent overheating of critical components such as motors.

Although sensors used in active exoskeletons provide significant benefits, their performance and durability can be affected by mechanical wear, temperature variations, moisture, shocks, and prolonged use, leading to inaccurate readings or failures [15].

The durability and sustained performance of exoskeleton-type rehabilitation systems are influenced by multiple factors, particularly the materials from which they are manufactured, the placement and integration of sensors and actuators, and operating conditions. Maintaining optimal performance and functionality involves regular calibration and, in certain situations, replacement of components. Moreover, proper sensor placement and individualized calibration are essential for obtaining reliable measurements, taking into account differences in muscle physiology among users. Additionally, components configuration and integration play a key role in ensuring patients comfort and the system's resistance to wear during intensive use. The implementation of strength materials is also essential both for increasing durability and for reducing production costs.

To extend the lifespan of exoskeleton-type rehabilitation systems, the main objective of the authors' research was to improve the protection of sensors against external factors such as moisture, mechanical shocks, and wear by embedding them into the exoskeleton structure and strategically positioning them within the system components. This approach involved incorporation of biocompatible materials with enhanced tribological properties, including high hardness and elasticity, in order to ensure enhanced durability and long-term operational efficiency. Therefore, the project aimed to verify whether sensor integration within the structure effectively enhances protection. A secondary objective was the tribological characterization of both the exoskeleton materials and the sensor coating materials, in order to identify the optimal material that provide maximum wear resistance, improved protection, and increased system lifespan.

Such a tribological characterization is presented in this article, carried out with the aim of determining the degree of surface destruction of a coating used to protect force sensors in exoskeleton systems.

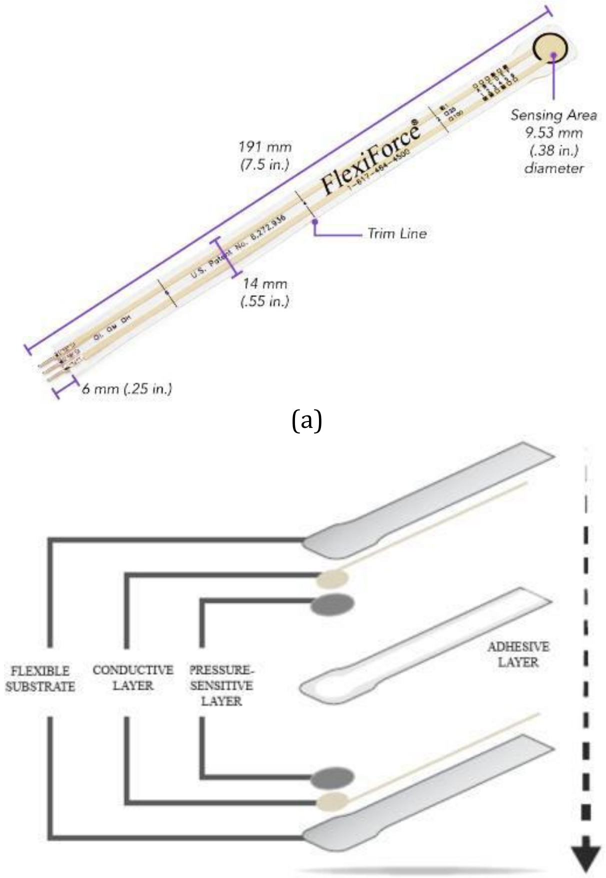
2. Experimental Methods and Materials

2.1. Analysed sensors

FlexiForce A201 tactile force sensors produced by TESKAN (Figure 1a) were selected for testing because they are widely used for lower limb exoskeletons. These are realized by using strain-resistive ink deposited on a thin and flexible polyethylene substrate. Also, they have simple interface circuits which reduce complexity and mechanical load.

The FlexiForce A201 sensor is a pressure-sensitive circuit that can measure the force between nearly any two contacting surfaces and is sufficiently durable for use in a wide range of environments. [16]

The sensor is composed of two substrate layers, typically made of polyester. Each layer is coated with a conductive material, such as silver, covered with a layer sensitive to pressure. The two substrates are then bonded together using an adhesive to form the complete sensor structure. The silver-coated region positioned over the pressure-sensitive layer forms the active force-sensing region. This conductive layer extends from this region to the opposite end of the sensor, creating the electrical leads (Figure 1b). [17].



(a)

(b)

Figure 1: (a) FlexiForce A201 force sensor. [16]; (b) Structure of the FlexiForce A201 force sensor. [17]

2.2. Technical-Functional Testing System

Technical and functional tests were conducted with a Instron 8872 servo-hydraulic system for fatigue testing in order to realize the characterization of the FlexiForce A201 sensors in real-time, within a force interval of 111 N–1112 N.

The sensors were mounted on a polyamide support (Figure 2), a material that is commonly used in exoskeletons structure, in order to better evaluate its mechanical resistance, also taking into account that the applied tests may have a detrimental effect on the substrate on which the sensor is installed.

Figure 2: FlexiForce A201 force sensor installed on the Instron 8872 fatigue testing system.

A series of 5 measurements was carried out at different force levels to achieve a comprehensive characterization of the tactile force sensors used in the project. Forces with values of 300 N, 600 N, 1000 N, and 1100 N were applied to the sensor contact surface at a frequency corresponding to normal human gait of approximately 1 Hz [18] over 100 cycles, in order to establish a reference sensor's signal for subsequent tests.

2.3. Coating Materials

The tests were conducted on the FlexiForce A201 force sensors coated with various biocompatible materials in order to identify a coating that offers protection to the sensors and improves the tribological performance of an exoskeleton that uses these sensors. The materials selected for evaluation are commonly used in exoskeleton-type systems, namely polyethylene (PE) and ethylene-vinyl acetate (EVA).

Polyethylene (PE) is a polymer composed of saturated hydrocarbons with high molecular weight. PE is a water-resistant, thermoplastic, flexible, and durable material with excellent resistance to chemical agents compared to many other polymers. [19] All common types of polyethylene, like high-density polyethylene (HDPE) and low-density polyethylene (LDPE), have superior properties. The first type is a rigid material with a crystalline structure, the second one being significantly more flexible, and presenting a high ductility. In general, the amorphous form of PE is harder and more soluble, while the crystalline PE is more elastic and less soluble. Due to this combination of properties, PE is widely used across multiple fields, particularly in the medical domain for manufacturing rehabilitation systems like prostheses, and various instruments, such as catheters and syringes.

Ethylene-vinyl acetate (EVA) is a commonly used foam material obtained by copolymerizing ethylene with vinyl acetate, with a typical vinyl acetate content ranging between 10% and 40% in a single sheet. Important properties of EVA foam are resistance moisture, shock damping, and high thermal insulation capability, giving it a long-term durability. The fact that EVA preserves flexibility under low-temperature conditions, makes it suitable for applications that require both wear resistance and flexibility. The high friction coefficient of EVA enhances adhesion, and stability, making it particularly valuable in applications where slip resistance and secure fixation are essential. Due to these properties, EVA is widely used in footwear, sports equipment, and industrial systems, as well as in the medical field, where its flexibility and chemical resistance support the manufacture of surgical instruments. [20]

2.4. Characterization Systems

The surface structure of the uncoated and coated sensors, before and after the functional tests, was investigated by atomic force microscopy, using a NTEGRA Probe NanoLaboratory NT – MDT microscope [21]

The investigation involved scanning of 50 × 50 μm damaged area from the sensors surface. The obtained images were processed and analysed using a special software of the system - Nova SPM. 3D surface topography maps were generated, allowing a more precise evaluation of surface uniformity. At the same time, key tribological parameters were automatically recorded, including average roughness (Ra), and surface skewness (Rsk).

Roughness (Ra) is the high-frequency component of micro-irregularities, distinct from the geometric shape deviations (waviness). The average roughness is the arithmetic mean of the absolute deviations of the profile from the mean line.

Surface skewness (Rsk) evaluates the degree of asymmetry in a distribution. It has a negative value if the distribution is asymmetrically skewed to the left or a positive value if the distribution is asymmetrically skewed to the right. A surface skewness with a value equal to zero defines a symmetric distribution.

3. Results and Discussions

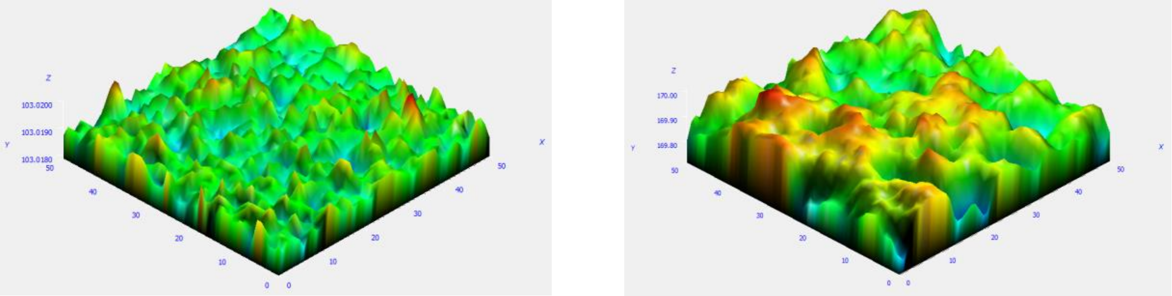
3.1. Topography of Sensors Surfaces

3D surface topography maps were analysed in order to evaluate the wear of the surfaces of the FlexiForce

A201 force sensors prior to and following the functional tests. In order to determine the protection capacity of the tested materials, these types of maps were also realized for both uncoated sensors, and sensors coated with PE or EVA layers of 0.5 mm, 1 mm, and 1.5 mm thicknesses. (Figure 3)

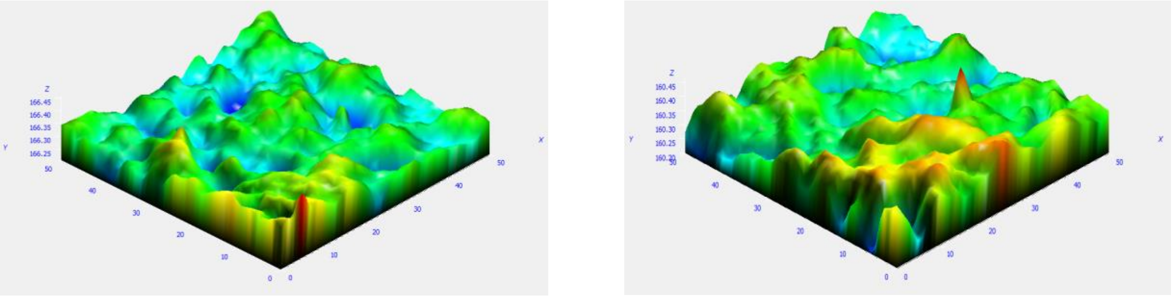
Sensors surfaces before functional testing

Uncoated sensors surface after the functional testing



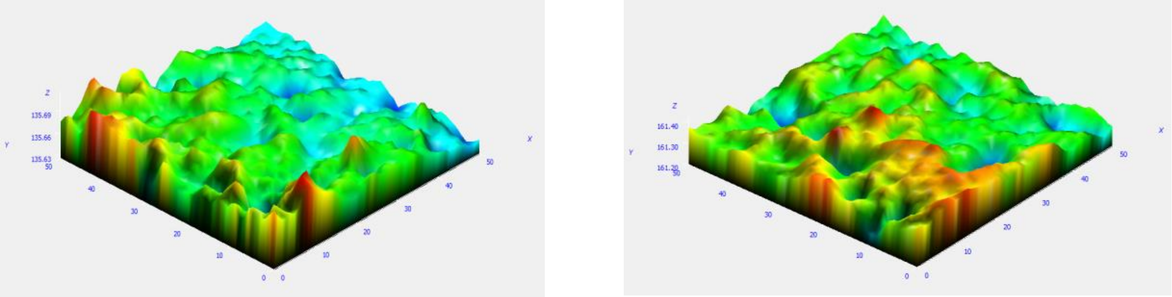
Sensors coated with EVA 0,5 mm

Sensors coated with PE 0,5 mm



Sensors coated with EVA 1 mm

Sensors coated with PE 1 mm



Sensors coated with EVA 1,5 mm

Sensors coated with PE 1,5 mm

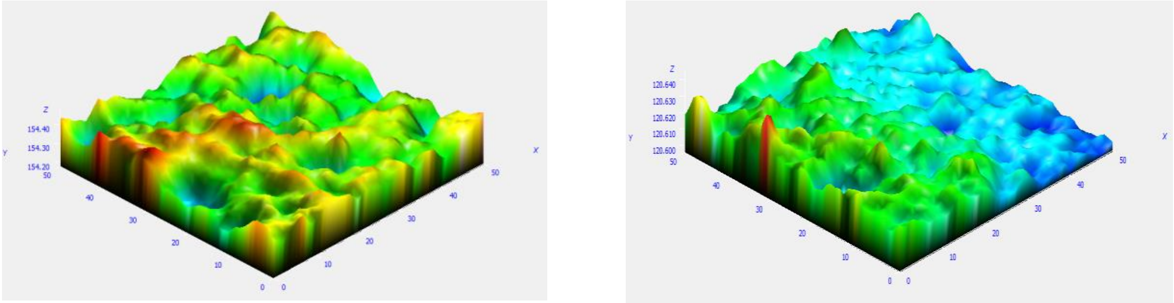


Figure 3: 3D surface topography maps of the surfaces of the FlexiForce A201 force sensors prior to and following the functional tests.

It can be observed that the sensors' surfaces undergo variable deformation after 100 testing cycles under each applied force, depending on the thickness of the coating layer. The uncoated sensors' surfaces exhibit significantly greater damage compared to the surfaces protected with both coating materials. Furthermore, appearance of deformations decreases as the coating layers thickness increases, EVA providing superior protective performance in comparison with PE.

3.2. Tribological Characterization

Following the tribological characterization of the functionally tested force sensors, important tribological parameters were obtained, which help determine the wear degree of their surface.

It is primarily about roughness, a parameter that characterizes the state of roughness of a surface, being defined by the microscopic irregularities on that surface, the asperities, the high-frequency ridges and valleys.

The surface's roughness values of the uncoated sensor and of the thin layers used for coating, before and after the technical-functional testing are presented in Table 1.

Table 1. Roughness values of the sensor's surface and of the coating layers after functional testing

Layer thickness (mm)	Roughness (nm)	
	EVA	PE
0	43.7908	43.7908
0.5	29.1767	37.6792
1	11.5625	33.8923
1.5	4.04769	6.46258

Thus, variations of the surface's roughness after coating the sensor were observed depending on the material and its layer thickness. The roughness decreases with increasing layer thickness for both materials, but the values of the EVA layer surfaces are lower than those of the PE layer surfaces. (Figure 4)

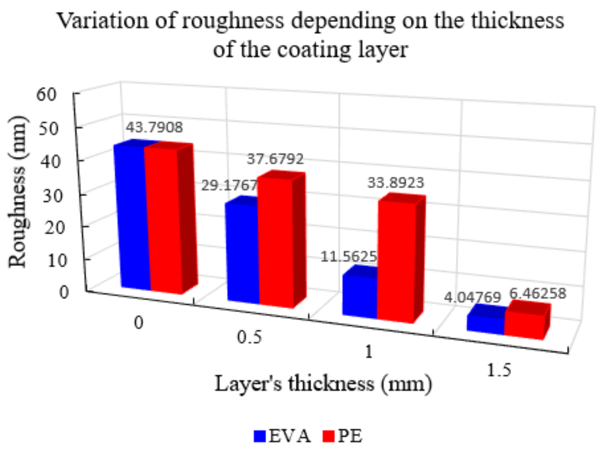


Figure 4: Variation of roughness depending on the thickness of the coating layers.

In percentage terms, this decrease had a very large variation, within a wide range of values, also taking into account possible errors of the functional testing device. (Figure 5)

Surface skewness is another important parameter that characterizes the shape of the existing distribution. In the case of both tested materials, there were changes in surface skewness, much more varied in the case of the PE layer than in the EVA one.

From the analysis of all the tribological characterization results obtained, it was observed that the 1.5 mm thick EVA layer exhibits increased resistance, being able to provide better protection and a longer lifespan of the sensor surface, compared to the PE layer. The final result of this study is that the EVA material is more useful for protecting sensors used in the structure of exoskeleton-type medical recovery systems.

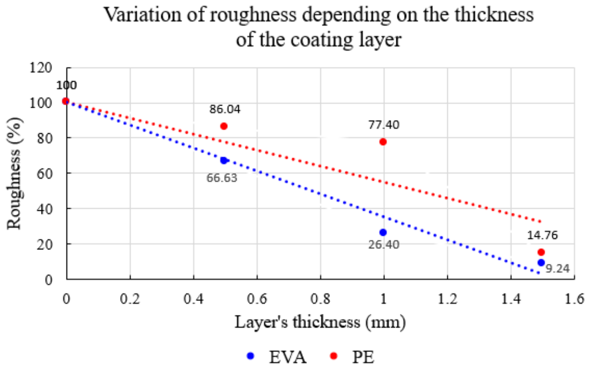


Figure 5: Procentual variation of roughness depending on the thickness of the coating layers.

4. Conclusions

The realized researches aimed to increase the wear resistance of sensors used in exoskeleton-type rehabilitation systems. The sensors usually used in these types of medical systems were subjected to technical-functional testing under the application of forces with different values, and, subsequently characterized through micro-/nanotopographical analyses.

Two biocompatible materials – polyethylene (PE) and ethylene-vinyl acetate (EVA) – were used and tested as protective layers, with different thicknesses.

The main conclusion of the study is that sensors' coatings provide effective protection against wear, extend life, and ensure reliable operation, with the 1.5 mm thick EVA layer offering the highest level of protection among the tested materials.

Starting from these results, the future work will focus on the technical and functional evaluation of the two materials under conditions closer to real operating environments, following the testing of a sensory network coated with these materials and inserted into exoskeleton structures applications.

Other materials that have different properties will be also tested, in order to assess whether there are materials that have superior tribological characteristics, capable of providing enhanced protection to the sensors from the exoskeletons' structure.

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