Biomimetic Tactile Sensing for Hannes Anthropomorphic Prosthetic Hand

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***Abstract*— A prosthetic device replicating the human hand capabilities is very challenging to achieve, not only for the intrinsic nature of the very complex movements, anthropomorphism, and aesthetics but also for the sophisticated capabilities that its net of receptors offers from the somatosensory perspective. Therefore, providing seamless human hand capabilities in a single device is still an open topic. Hannes Hand prosthesis exemplifies advancements in prosthetic technology, and, for this research activity, a preliminary integration of P(VDF-TrFE) piezoelectric sensors enhances novel tactile sensing capabilities. This study focuses on the sensorization of the Hannes Hand, aiming to bridge the gap between human hand functionalities and prosthetic performance. We present a preliminary implementation of sensor arrays embedded within the prosthetic glove, ensuring high sensitivity and responsiveness. Our approach aims at emphasizing sensor fusion toward the development of comprehensive feedback and intuitive control. Through a preliminary comparison analysis with human mechanoreceptors, we highlight the effectiveness of our piezoelectric sensors in replicating rapid adaptive behaviours, crucial for dynamic interaction with the environment.**

Keywords—Tactile, Prosthetics, Fast Adaptive, Piezoelectric.

I. Introduction

The human hand possesses remarkable capabilities, enabling individuals to interact with the environment. These capabilities are the result of a highly evolved biological system that seamlessly integrates sensory perception, motor control, and cognitive processes. Replicating the capabilities of the human hand in prosthetic devices is very challenging, aiming to provide individuals with limb loss a controllable, wearable, and long-term solution that supports their needs and enhances their quality of life [1]. To achieve this goal, prosthetic devices must go beyond basic mechanical functionalities. This requires the development of closed-loop systems with human-machine interfaces that enable bidirectional communication between the user and the prosthesis [2]. By integrating advanced technologies such as sensor fusion and tactile feedback, prosthetic hands can offer new features and capabilities that approach the level of functionality and sensitivity exhibited by the human hand. To this extent, sensor-fusion plays a crucial role in enhancing the capabilities of prosthetic hands: different information can be used to enable intuitive control of the prosthetic hand, allowing users to perform a wide range of tasks with precision and dexterity. Moreover, sensor fusion facilitates the development of closed-loop control systems that can adapt to the user's intentions and provide natural and responsive prosthetic functionality [1]. Although significant advancements have been made, many existing solutions lack fully integrated and embedded sensor technologies. Wearable and glove-style solutions [3] are currently prevalent, offering basic functionality but often falling short in providing the full range of capabilities and sensory feedback. Consequently, there is a growing need for prosthetic hands with tactile sensors. Tactile sensing technologies are fundamental in replicating the human sense of touch in artificial systems. These sensors function through various transduction methods, including capacitive [4], piezoresistive [5], piezoelectric [6] and optical sensing [7]. Capacitive sensors excel in spatial resolution [4], while piezoresistive sensors offer high durability and force sensitivity [5]. Piezoelectric sensors detect high-frequency vibrations [6], and optical sensors provide high sensitivity through light detection [7]. Biomimetic tactile sensors, inspired by human skin, represent the cutting edge, aiming to achieve the most natural and versatile artificial touch [8]. These advancements in tactile sensing hold great potential for revolutionizing robotics and prosthetics, leading to more intuitive and immersive human-machine interactions. One approach could be to focus on specific hand sensing capabilities. Therefore, targeting specific human hand functionalities, i.e. the fast adaptive human mechanoreceptors, can help humans in recognizing the start and stop of the contact (therefore the beginning and the end of an interaction with an object). This specific feature is provided by precise mechanoreceptors namely, Pacinian corpuscles (sensitive to high-frequency vibrations) and Meissner's corpuscles (sensitive to light touch). Rapid adaptation is achieved through a combination of receptor fatigue and neural inhibition [9]. This rapid decrease in firing rate after the initial stimulation enables us to focus on the dynamic aspects of touch, such as object texture and movement across our skin, while filtering out the overwhelming sensation of constant pressure [10]. In this context, the Hannes Hand [11] represents a promising advancement in the field of prosthetics therefore,

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incorporating piezoelectric sensing technologies and embracing the principles of data fusion, could bridge the gap between human hand capabilities and prosthetic functionality. In this paper we explore a preliminary sensorization on the Hannes Hand, focusing on a piezoelectric based sensor architecture integrated within the hand glove which can be easily translated to other prosthetic hand devices. Through comprehensive sensor integration, the Hannes Hand aims to deliver a more immersive and intuitive prosthetic experience, empowering users with enhanced control and sensory perception. The paper is organized as follows: Section II the material and methods, Section III results and Section IV discuss and conclusions.

II. MATERIAL AND METHODS

In this Section we first present the sensorization of the Hannes hand using P(VDF-TrFE) piezoelectric sensors (sub-section II.A). Following, we present the object selection (sub-section II.B) thought which we preliminary tested our setup. In II.C we describe the testbench. Finally, II.d describes the testing methodology adopted to qualitatively validate the overall development.

A. Tactile sensing integrated within the hand glove

This study involved the two main functional blocks. The first one is represented by the piezoelectric sensing arrays integrated within the thumb, index, and middle fingertips' hand gloves, and the interface electronics (IE) to collect the voltage of the sensors (sub-section II.A). Sensorization of the index finger only was used for this experiment. The second block represents the host PC through which two GUIs run in parallel: the first one is the HannesApp, used to control and collect the data of the hand and the second one, a LabView GUI, used to log and analyse the data of the IE.

1) The Sensing system: general overview

The proposed sensor technology was previously used in robotic applications [12]. Each sensing patch consists of 8 sensing units of 1 mm diameter each and 0.6 cm center-to-center pith. What characterizes these sensors the most is their frequency bandwidth that ranges from 0.5 Hz to 1 KHz. The voltage output of the sensors is processed using an interface electronics (IE) equipped with ARM Cortex M0 microcontroller and a DDC232 analog-to-digital converter, with a 2K Samples/sec as a sampling rate. As consequence, it was decided to integrate the sensing arrays on the Hannes hand to collect their response for targeting a real use prosthetic application toward objects grasp (Figure 1). For this purpose, piezoelectric sensing patches were integrated but only the one on the index finger was used in this experiment.

2) Preparation of the sensing system on the prosthesis.

We used the Hannes hand [11][13] because of its intrinsic human-like biomimetic performances and capabilities. Therefore, improving this hand functionalities could play a key role. The sensing arrays were covered on both sides with conductive tape (Model tesa 60262, tesa) to reduce the sensitivity of the sensors against the noise, and external charges. The sensors were protected by adding a shielding layer using double sided-adhesive tape (Model 3 M 9485, 3 M). The IE was placed in a shielded box (see Figure 2). The glove is composed of an inner transparent glove and an outer human-like one. The shielded sensor was sandwiched between the two gloves by first integrating it on the inner glove, stabilized with silicone rubber adhesive (Sil Proxy) and then through a thin layer of the same silicone adhesive rubber on the sensors and fit the outer glove. As a result, the sensors were fixed on the hand glove obtaining an integrated sensing system for prosthetic use easy to be removed and donned on the hand (Figure 1).

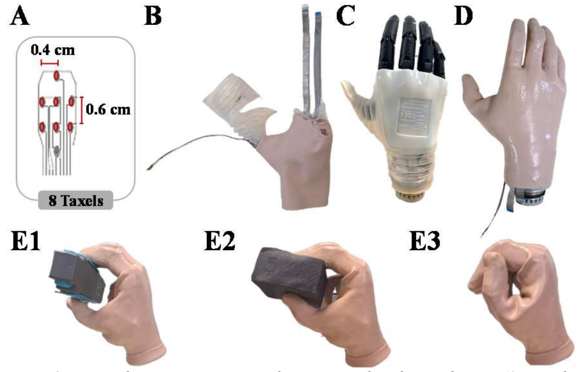


Figure 1: Piezoelectric sensing on the Hannes hand prosthesis: A) Tactile sensing patch, B) Fully integrated sensorized glove, C) Hannes hand with D) the sensorized glove E1) Dynamometer grasp, E2) Cube5, E3) empty grasps.

3) Human oriented processing of tactile data

We employed the Izhikevich spiking model [14] to encode the tactile signals and convert it to spikes. In particular, We chose the parameters of the Izhikevich neuron to emulate the behaviour of the regular spiking neurons [15]. Each tactile signal is applied as an input current to the spiking model after removing the dc offset and followed by the multiplication with a gain factor (gf). A gain factor of 700 \ohm is chosen to balance between the sparsity and high firing rate that could be emitted from static signals (i.e. noise). The input current depolarizes the voltage membrane of the Izhikevich model until reaching a threshold defined equal to 30 mv, and emitting a spike followed by resetting its value to a resting value of -65 mv.

B. Objects selections

To test and assess the sensing system integrated on Hannes 3 type of grasps were chosen, grasp of hard, soft object, and empty grasp. The three grasps were selected to highlight the sensors behaviour by generalizing a standard prosthetic use case scenario. For the sake of visualizing and measuring the grasp force while testing the hard object, a Venier Hand Dynamometer [16] has been used. The soft object was a 3D printed cube, this object refers to a set of object used in previous work [12], this object has a filling percentage of 5% made by Filaflex material, Thermoplastic Polyurethane (TPU) that presents a large elasticity.

C. Testbench design

An ad-hoc test bench was developed (Figure 2) composed of movable parallel arms and a two-cuff system acting as a holder. Hannes hand was fixed at the base of the test bench, in such way the fingertips had an impact on the objects when grasping. Hannes was connected to the PC through CAN-USB adapter and controlled through HannesApp, which also allowed data acquisition (current consumption of the DC motor and the related encoder position). For the sensing side, the tactile sensors signals were collected through the IE which interfaced to the host PC through

USB connection. A LabView Gui was used to log and display the piezoelectric sensors data.

D. *Testing methodology*

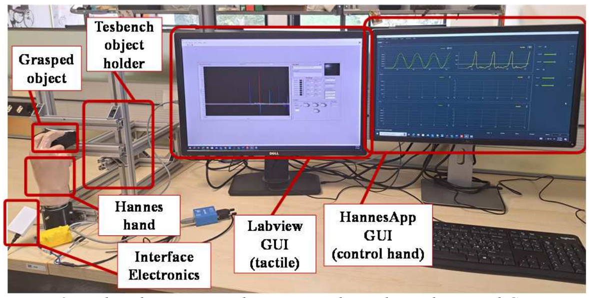


Figure 2: Tesbench presenting the sensorized Hand prosthesis and GUIs.

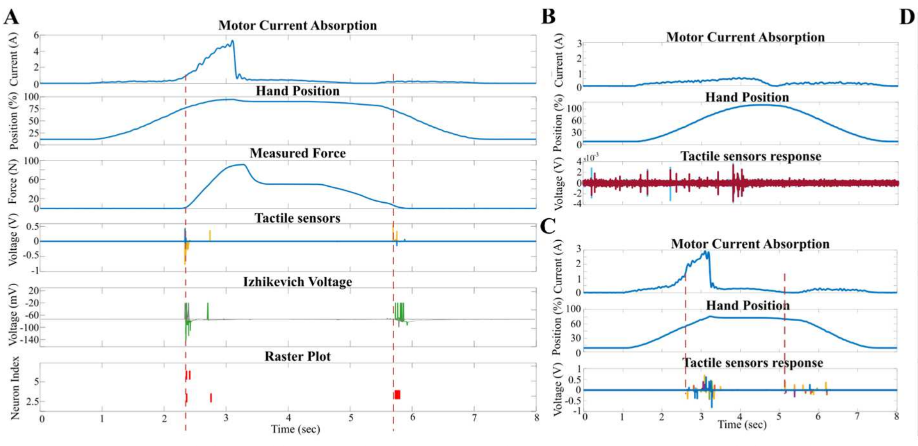
To generate the variability of the data, five grasps were applied with a set of 3 different frequencies of closing (Hz) [0.3, 0.4, 0.5]. Three grasping scenarios were identified: a hard object (Grasp dynamometer), a soft material (Cube 5), and an empty grasp (Figure 1). In each scenario five grasps were applied per frequency to study the complementarity between the hand data and tactile data during the grasp.

III. Results

A qualitative analysis is conducted for preliminary evaluating the integrated sub-systems behaviours: the hand prosthesis and the sensing system. Figure 3 shows an example of the experiment at a grasping frequency of 0.3 Hz during the grasp of a rigid (Figure 3.A), an empty grasp (Figure 3.B) and soft object (Figure 3.C). As shown in Current subplots, the max hand's DC motor current absorption varies based on the object grasped. The position subplot reflects the behaviour of the position reference provided by the HannesGUI to the hand. Therefore, also the sensing response resulted in differing according to the hand-object interaction. 3.A presents the response while grasping the Vernier Dynamometer: according to current absorption (max value of 5800mA) the dynamometer measures real grasping force (max grasp force on 98 N) and highlight's the effect of the overcurrent threshold. The drop happening after reaching the maximum results obvious due to the hardware and software protections that prevent hand damages from over current. Moreover, piezoelectric response and current consumption reflects similar behaviour till the grasp movement stops. In addition, the force graph and piezoelectric response ended at the same time indicating the end of contact between the dynamometer and the hand and the hand position ended after 0.5 s representing the time taken to move the fingers between the last moment of contact with the object and the opening hand position reference. In 3.B, as the hand performed an empty grasp, information on the hand side only is provided (no interaction with any object is perceived by the sensorized glove). Current absorption of about 600 mA corresponds to an empty grasp movement in which the hand fingers are freely moving in the space. In this case, as the reference position increases, the current consumption increases because of the intrinsic mechanical lever arms of the fingers and the return wire mechanisms (springs + tendon) plus the natural elasticity of the glove which both creates an opposition while flexing the fingers. On the other hand, when the position decreases, the DC motor releases the tendons (both master and slaves wires) therefore not creating opposition but facilitating the finger flexion. Therefore, the second bell shaped current absorption is the nominal current absorption of the DC motor combined with a planetary gearbox at its nominal behaviour. In 3.C, soft object (Cube5) grasp, the current absorption reaches 3500 mA as contact occurs with the thumb, index, and middle fingers. Meanwhile with the beginning of the steep climb of the current consumption, the piezoelectric starts responding, indicating the beginning of the contact. The response period representing the grasp of the object is simultaneous with the time from the increase in current consumption till reaching the threshold and having the overcurrent cut off. As for 3.A, tactile sub-plots representing the 8 channels on the index, shows that the variation in the signals provide different response as the angle of contact and position of each sensing unit is different therefore the contact of each unit occurs in different time instants on the object. From position sub-plot, the release starting at t=3.7 sec, provides a different piezoelectric response shape for each channel, as for the current consumption the bell representing the release will not exceed 600 mA as for 3.A.

IV. Conclusion and Discussion

The primary aim of this paper was to investigate the sensorization of the Hannes hand using P(VDF-TrFE) piezoelectric sensors and to compare the tactile response of these sensors with the rapid adaptive behaviour of human mechanoreceptors (Meissner corpuscle and Pacinian corpuscle). The integration of these sensors in a prosthetic



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	Meissner	Pacinian	Merkel	Ruffini	Piezoelectric sensors
Type	RA-I	RA-II	SA-I	SA-II	RA-I and RA-II
Adaptation rate	Fast	Fast	Slow	Slow	Fast
Location	Shallow	Deep	Shallow	Deep	Shallow
Stimuli frequency [Hz]	10-200	70-1000	0.4-100	0.4-100	0.5-1000
Density (units/cm²)	140	20	70	10	8 customizable
Spatial resolution (mm)	3-4	10+	0.5	7+	1 customizable
Functions	Object slip, Light touch, texture	High-Frequency vibrations	Static force with high resolution	Tension deep in the skin and fascia	Object slip, Light touch, texture, high-frequency vibrations
Receptive field (RF)	Small and sharp 3-5mm	Very large and diffuse, >20 mm	Small and diffuse 2-3 mm	Large and diffuse, 10-15 mm	3.5 - 4 cm customizable

Figure 3: Sensorized glove and hand signals while grasping A) Vernier Dynamometer – rigid object, B) empty grasp and C) cube 5 – soft object at frequency 0.3 Hz.

hand represents a significant step toward achieving a more natural and effective sensory mechanism for prosthetic users. Human mechanoreceptors, particularly the Pacinian and Meissner's corpuscles, exhibit rapid adaptation, allowing the human hand to perceive dynamic changes in pressure, texture, and movement. Our preliminary analysis demonstrates that the piezoelectric sensors can effectively detect the beginning and end of contact while grasping objects, which is crucial for grasp tasks (Figure 3). The sensors' responses were consistent with changes in current consumption, indicating their ability to provide real-time information while the hand interacts with objects. However, unlike human mechanoreceptors, the piezoelectric sensors do not reduce their response after the initial stimulus. This continuous feedback can be advantageous for certain applications, but it also necessitates the development of advanced signal processing techniques to emulate the adaptive filtering observed in human touch. To this extent, the last two subplots of Figure 3.A presents a preliminary investigation running the Izhikevich spiking model to encode the tactile signals and convert it to spikes, trying mimicking the natural desensitization process as proposed in [17]. Overall, the sensorization system offers several benefits. Firstly, its wearability, as the combination of the transparent inner glove and the outer glove resembling human skin, simplify donning and doffing by ensuring comfort and convenience for the wearer. Secondly, as the piezoelectric sensors is securely embedded between the using silicone rubber gloves are protected against external therefore improving robustness. Moreover, the system's aesthetic appeal is a significant advantage, as the hidden placement of the sensors between the gloves creates a visually seamless and natural appearance, fostering an embodiment feeling for the amputee [18]. Lastly, the system's translability, thanks to its modular design, allows for the efficient reuse of the sensorized gloves on other prosthetic devices, promoting cost-effectiveness and facilitating the widespread integration of tactile sensing capabilities. In conclusion, the sensorization of the Hannes hand with P(VDF-TrFE) piezoelectric sensors presents a significant advancement in prosthetic technology, offering improved control and sensory feedback. Future work will focus on data fusion and machine learning techniques to create a closed-loop control system that can adapt to the user's intentions and provide a more intuitive prosthetic experience. Additionally, exploring different types of tactile sensors and their combinations may provide a more comprehensive solution to achieving human-like touch in prosthetic devices. By addressing these challenges, we could move closer to prosthetic hands that not only restore function but also provide a sensory experience that closely mirrors the natural capabilities of the human hand.

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