SINTEC

SOFT INTELLIGENCE EPIDERMAL COMMUNICATION PLATFORM

SINTEC FINAL WORKSHOP

Smart Bioelectronic and Wearable Systems

26-28 April 2023 | Uppsala University (Sweden)

PROCEEDINGS

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

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SINTEC Final Workshop
"Smart Bioelectronic and Wearable Systems"

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Welcome to the SINTEC Final Workshop on Smart Bioelectronic and Wearable Systems!

The aim is to highlight European research focused on the ultra-flexible, stretchable, soft and conformal technologies, and networking with companies and European funded projects to discover future opportunities in the stretchable electronics market.

Building on the success of previous events on Micro-Nano-Bio Systems (MNBS) and its European Commission Workshops on 'Smart Bioelectronic and Wearable Systems', the Workshop covers the topics of Bioelectronics; Stretchable and conformal electronics; Wearable sensors and actuators; Smart patches and clothing; Wearables for sports and healthcare application; Intra-body communication; and Network solutions for wearable health and sport monitoring.

Just as in the Workshops of MNBS, the event will once again:

- bring together the value chain of the soft and ultra-flexible system integration fields of endeavour;
- provide opportunity for synergies, new topics, ideas for collaboration, exchange, and networking.

We hope that the workshop will be an excellent opportunity to:

- diffuse and exchange information on R&D results and innovative solutions from EU-funded projects and other initiatives in Europe;

- identify synergies and possible collaborations from R&D to Innovation.

The event will include oral and poster presentations from EU-funded and other Research & Innovation projects, bringing technologies and solution providers closer together in the emerging field of ultra-flexible, stretchable, soft and conformal technologies.

We hope that you will find it interesting and that you find plenty of time and opportunity to network with friends and novel acquaintances, in an inspiring environment!

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Klas Hjort

SINTEC Project Coordinator

Prof. Hjort is experienced in advanced microengineering. Recently, his focus has been heterogeneous microsystems on stainless steel, flexible foils and elastic substrates; for biomedicine and wireless sensor and actuator nodes. He is co-ordinator of the H2020 projects SINTEC on soft and stretchable printed circuit boards for wireless smart patches and SOMIRO on autonomous swimming soft micro robots that only require energy from the sun.

Isella Vicini

SINTEC Project Manager

Isella Vicini is the Director of the European Funding Development of Warrant Hub S.p.A and the CEO and founder of beWarrant, a Belgian consultancy company that provides support on European Funding opportunities. She has a wide experience in the EC Research and Innovation programmes, like Horizon 2020 and LIFE Programme. Since the First Framework Program (1985), she works in the European Project Design field, taking care of the complete cycle of a project: from the analysis of the sectorial policies to the conclusion of the research and innovation project. She currently manages a team of 16 people and her European Funding Development provides 80 consultancy services per year, it is involved in 51 projects and it manages 151 million euros Horizon 2020 grant. Isella is the Project Coordinator of the EU funded project Repair3D and the founder and Dissemination Manager of ECHOES, the EC Cluster on Cultural Heritage.

Gustaf Mårtensson

SINTEC Project partner

Gustaf has a M.Sc. in Engineering Physics from the Royal Institute of Technology (KTH) in Stockholm, Sweden. He continued his studies in the realm of fluid mechanics and received his Ph.D. in 2006 from KTH. Gustaf divides his time between rolls as an Expert of Complex Fluids at Mycronic AB and an affiliated researcher at the School of Chemistry, Biotechnology and Health at the Royal Institute of Technology in Sweden.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

SINTEC: Soft intelligence epidermal communication platform

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SINTEC is a Horizon 2020 funded project that will provide soft, sticky and stretchable sensor patches that can be used multiple times and at longer periods. With its dynamic compliance and water repellent permeable encapsulation it withstands vigorous action, sweating and water; making it ideal for an active life. Our vision of extensible smart patches is a non-invasive support system that can be used all the time, allowing an active elderly person to be warned when their health is slowly deteriorating (for example in case of heart or muscle problems) or to help a person recovering in a faster rehabilitation with sensory support and recommendations from an app without having to be in a physiotherapy institute for too long (eg. after a long illness, stroke or trauma).

The aim of SINTEC is to advance a rigid-stretch PCB technology with stretchable substrate and liquid alloy, and to demonstrate its usability in complex applications, involving wearable sensing, embedded processing, and Fat-IBC. This will substantiate the advantages with this rigid-stretch technology and its improvement area. Industrial manufacturability and cost/scaling issues will be investigated. Its unique features will enable a ground breaking intra body communication technique that provides secure communication at large bandwidth and low power, allowing for multiplex sensoric inputs from many sensor nodes on the body.

The main advantages should be in comfort and that the sensors do not move so much relative to the skin. Hence, its major impact will not be in replacing other wearables but rather providing novel capability.

To demonstrate the advantages of the novel technology, SINTEC will apply it in clinical environment and in athletics performance evaluation.

Acknowledgment
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984

Oral presentations
27th April 2023

ABSTRACTS

Spray-printed stretchable microelectrode array of supercooled liquid gallium

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By controlling the surrounding of supercooled liquid Ga (SLGa), so that no surrounding material has similar crystal structure or a higher surface energy, it was possible to keep it liquid at temperatures much lower than its freezing point. Hence, it is possible to manufacture stretchable electronics with pure Ga. In addition, the interior of microscale particles remained liquid when produced by sonication of SLGa. Spray printing of ink of such particles can conformally pattern Ga on a rough surface, e.g., to build a stretchable array of SLGa microelectrodes. We investigated the crystallization triggering by temperature, circuit cross-section, mechanical impact, and surface energy of nucleation agents. For electronic circuits, the encapsulating PDMS has lower surface energy but the metal contacts of conventional components have higher surface energy than Ga. We solved this by having a conductive intermediate material of lower surface energy, using Galinstan or graphene ink. By coating contacts with a graphene layer, we demonstrated stretchable SLGa electronics at -22 °C. However, when using Galinstan as an intermediate, the Ga froze with the Galinstan at -19 °C, since the solid Galinstan has a similar crystal structure. Finally, we manufactured a stretchable electrode array of 33 SLGa microelectrodes of 0.5 mm in diameter. The microelectrode was enough small and rough to withstand the risk of rupture and leakage at normal handling, leaving no stains after contact with the skin. More importantly, it had a low and stable impedance even in water. This may provide a solution to the existing problem of losing signal of commercial gel electrodes when submerged in water, due to electrolyte dilution and hydrogel swelling. A wearable smart patch with two SLGa electrode arrays could record human ECG signals in cold lake water.

We acknowledge funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 824984 and from the Swedish Research Council under grant agreement No 2017-03801.

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Design and technologies for high throughput manufacturing of medical wearable electronics

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Living in digital era has revolutionized conventional health monitoring and diagnostic practices. Emergence of high-performance, miniaturized microelectronic components enables development of wearable sensors that can be worn for days and weeks for continuous monitoring of vital signs and detection of possible health conditions. On the other hand, advances in stretchable electronics and hybrid system integration facilitate production of elastic and soft skin patch devices that can conform to skin deformities while providing maximum wear comfort. Over the last decade, there have been significant progress in lab-scale development of different type of wearable sensors including skin patches and e-tattoos. However, design for manufacturability aspects were not addressed sufficiently. Herein, we discuss the process flow development and hybrid system integration for scalable manufacture of wearable skin patch devices at VTT.

In the context of this abstract, a hybrid electronics system is referred to an integrated electronic device where conventional rigid microelectronic components are interfaced to soft, flexible, and stretchable components and materials such as elastic substrate, stretchable conductive inks and flexible conductive adhesives. Depending on the target application and use case, the integration method can differ. In a use case [1], an elastic electrocardiography (ECG) patch was realized by direct assembly of rigid components (i.e. SoCs, capacitors, resistors, etc.) on 100 µm-thin stretchable TPU substrate. The manufacturing process was developed to be truly compatible with roll-to-roll (R2R) and sheet-to-sheet (S2S) processing, both for printing the circuit layout and assembly of the components. Integration of the components on the substrate was performed by automated pick up and place machinery.

In some use cases, a more sustainable approach is preferred where the electronics unit is detachable from the disposable skin patches. With this approach a single electronics unit can be reused for as many as disposable patches available. The hybrid devices are economically justified only if manufacturing of the disposable patch is cost efficient. This requires a processing methods where the skin patches can be produced at high volume using cost efficient process. At VTT, we piloted a fully roll-to-toll process for multilayer screen printing of patch circuit layout (i.e. ECG lead wires and electrodes) and conversion of materials into a fully integrated skin patch. Following the printing, the roll of printed layout on TPU is taken to VTT's pilot converting line to put together different elements of the skin patch. A typical roll-to-roll conversion process includes kiss cut, die cut, laser cut, and layer-by-layer lamination of the non-woven adhesive, printed layer (on TPU substrate), transfer adhesive, and skin adhesive. Achieving a seamless conversion flow requires careful system architecture of the whole wearable device, selection of proper materials and detailed conversion plan. A great benefit of piloting at R&D phase is the possibility of refining the design, materials, and processing steps to gain the optimum outcome.

Manufacturing and converting methods depend on the application and material selection. VTT uses various materials as substrate for stretchable electronics. In a recent study we demonstrated PMDS-based, multilayer e-tattoo with the overall thickness of 50 µm for collecting bio-potential signals [2]. The e-tattoo shows extreme conformity to skin deformation and provide ultimate wear comfort. The development process was designed to be compatible with both S2S and R2R manufacturing methods.

Moving toward greener and more sustainable printed electronics, VTT recently developed nanocellulosebased flexible substrate which degrades in soil and marine conditions [3]. The biodegradation process facilitates separation of the assembled electronic components from the substrate, leading to leaner recycling process after use.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Single-molecule bioelectronic sensor: improving reliability with machine learning approaches

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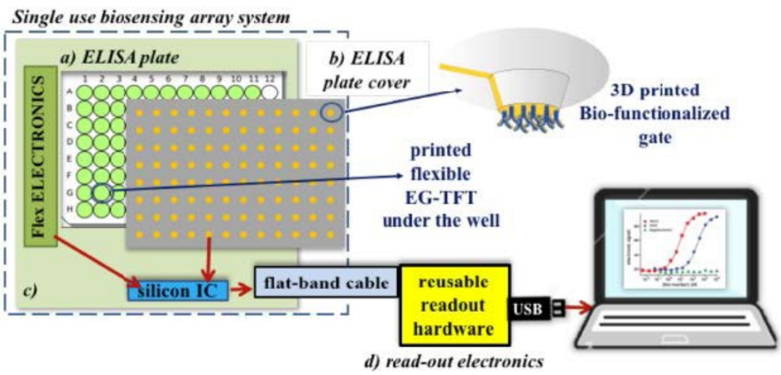
Digitizing biomarkers analysis by quantifying them at the single-molecule level is the new frontier for advancing the science of precision health. The enhancement of the technical capabilities of bioelectronics systems, by giving clinicians the possibility to rely on biomarkers quantifications down to the single-molecule, holds the potential to revolutionize the way healthcare is provided. Such an analytical tool will indeed enable clinicians to associate a biomarker tiniest increase to the progression of a disease, particularly at its early stage.[1] Eventually, physicians will be able to identify the very moment in which the illness state begins. Such an occurrence will enormously enhance their ability of curing diseases by supporting better prognosis and permitting the application of precise treatment methods. The single molecule bio-electronic smart system array for clinical testing - SiMBiT - technology has been developed within the blooming field of precision medicine, leveraging on the single molecule with large transistor (SiMoT)[2] lab-based technology that can perform single-molecule detection of both proteins and DNA bio-markers.[3,4] Specifically, the SiMBiT technology has lately developed the SiMoT lab-based device into a cost-effective portable prototype multiplexing array that integrates, with a modular approach, standard components and interfaces with novel materials and exhibits enhanced sensing capabilities. The SiMBiT prototype has proven its potency in early detection of pancreatic cancer, being capable to discriminate among low-grade and high-grade mucinous cyst's lesions in peripheral biofluids, such as plasma samples. In this perspective, machine learning approaches play a pivotal role in developing classifiers for a fast, reliable multiparametric biosensors output. Supervised model based on multivariate data processing has been undertaken to enable multiplexing, i.e. the simultaneous quantification of three biomarkers, namely MUC1 and CD55 proteins and KRAS DNA mutated sequence, in plasma and cysts' fluid samples. The main technological aspect of the SiMBiT device, with particular emphasis on the potency of machine learning approaches, will be discussed.



SiMBiT portable prototype.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Wearable Electronics based on Stretchable Nanocomposites

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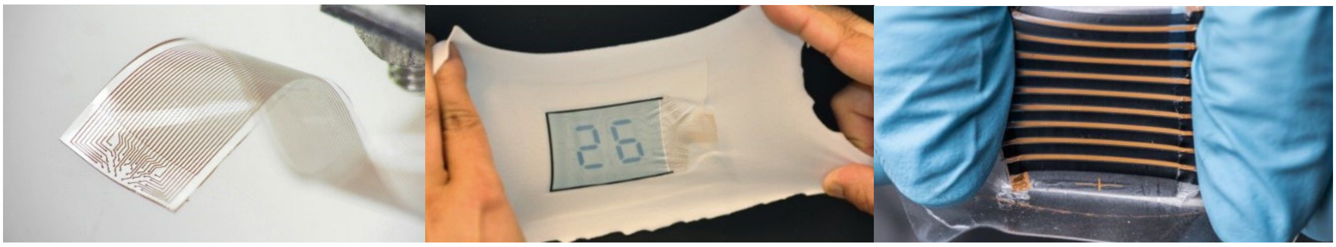
Stretchable electronics allows for seamless integration of electronics onto textiles, on skin, and inside the body. Depending on the application, soft and stretchable electronic materials can have a demanding set of requirements, including biocompatibility, specific mechanical and electromechanical properties, long-term stability, and good electrode performance. Within the Soft Electronics group [1] at Linköping University we have developed a variety of stretchable nanocomposite materials, along with specialized fabrication processes, to target applications from soft neural interfaces, to printed wearable devices and energy harvesting and storage. Here I will discuss the different types of stretchable nanocomposites we have developed, their properties, and suitable use. I will also emphasize the tailored processing routes of these materials, as soft nanocomposites come with certain processing challenges. Finally, I'll go into the various device concepts and applications areas we have explored in recent years, including printed wearable displays and transistors, soft neural interfaces for brain and nerves [2], and stretchable thermoelectric generators [3] and bio-based batteries.



Devices from left to right: stretchable high resolution neural electrode, printed stretchable display, stretchable thermoelectric generator.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Bio-Inspired Electronic Systems for Biomedics and Precision Agriculture

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Applications are demanding new approaches to electronic systems. The concept of running for obtaining the best performances in terms of speed and dimensions, that drove the electronic design in the last decades, is no more valid. The electronic systems are nowadays applied in very much different scenarios where sometimes it is not at all important the speed, but power consumption and reliability are the keys. It is strategic to find new approaches that must have an impact at system level, not on the single parts only, but on the global structure: the optimization is done as consequence of the choices related to how the single devices are working, associated to how they interact each other and they transmit the information. The two levels (system and device) are strictly related, and design choices have to be done looking at the system as a global entity to be optimised.

For optimising the aforementioned aspects, it is strategic the choice of the system level paradigm that will drive all the design choices. For these reasons, it is strategic to take inspiration from the biological systems, applying a merge of the techniques born in recent years and exploiting them for reaching the best tradeoff between quality, and so performances, and power consumption [1]. In the talk will be analysed solutions related to what is named Bio-Inspired Electronics, for applying biological paradigms in system optimisation.

As first consequence, it is possible to implement systems that work with digital signals, bringing an analog information, no more based on amplitude or bits, but on a time-based approach, as reported for specific applications in [2] and [3].

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Epidermal Sensors for Medical Diagnostics

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Epidermal bioelectronic devices show great promise in healthcare due to their ability to provide longitudinal monitoring as well as on-demand delivery to maintain optimal health status and evaluate patients' physical conditions.[1] Epidermal biosensors are at the center of this effort and offer a vast potential to revolutionize conventional diagnostics that uses traditional laboratory tests-based evaluations, usually called 'clinical labs,' that are slow and mainly require in-person visits and frequent invasive sampling if the long-term analysis is necessary.[2]

In this presentation, I will give a brief overview of our recently developed epidermal diagnostic approaches targeting various metabolites, hormones and microorganisms as well as some of skin physical and chemicals parameters to acquire better knowledge on early diagnosis and disease progression particularly for metabolic diseases and infections. This talk will summarize how to design epidermal sensors, integrated electronics and how to use them in clinical setting with our unique access to patient materials, which creates an unprecedented opportunity to address fundamental questions in medical diagnostics.[3-4]

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Biomass Derived Nanocellulose Based Electrodes for Simultaneously Ultrasound and Bio-Electronical Signals Recording

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A large population of motor disorder cases is caused by skeletal muscle disabilities.[1] A quantification of the muscle performance largely relies on the biofeedback information collection including measurements of myoelectric activity and imaging the muscle tissue. However, current evaluations are mostly relying on a single data collection, reduces the ability to understand association between activation and tissue movement. Here, we address this limitation with a new concept of biomass-derived nanocellulose/PEDOT:PSS electrodes capable to capture the electromyography (EMG) and ultrasound (US) images in a synchronized fashion (Figure 1). The idea enabled us to create high performance nanocellulose-based electrodes with good mechanical strength, US transparency and conductivity. The EMG signals, muscle fiber morphology and detected forces synchronized during muscle relaxation/contraction movement. The electrodes are portable to the commercial US device and wireless signal transition device, show great possibility to be commercialized. Overall, this work opens up new pathways for simultaneous recording of EMG signals and US images by using environmentally benign materials.

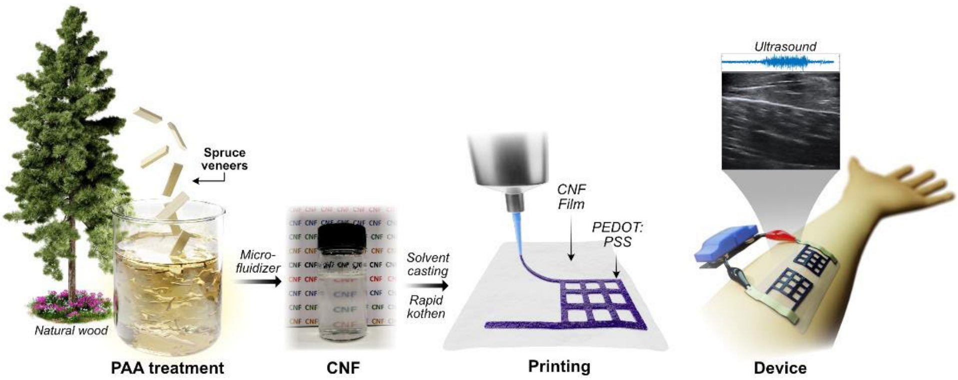

Figure 1. Schematic of CNF prepared from wood, conductive polymers printed on the surface of CNF film, and signals collecting of musculoskeletal tissue.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

The validity of a novel stretchable smart patch developed in connection with the SINTEC project for monitoring sports performance

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Although wearable technologies are being used more and more to monitor sports and health and are a leading worldwide trend in fitness [1, 2], currently available wearable sensors are often bulky and/or uncomfortable [3, 4] and suffer from poor fixation to the body, which compromises accuracy and can even lead to complete loss of data, especially in conjunction with extensive movement. These disadvantages can be circumvented by employing smart patches such as those developed within the SINTEC project, which are smaller and lighter (Figure 1) and thereby more comfortable when moving [3]. In addition, their adhesive attachment to the body holds smart patches firmly in place, thus providing high-quality biomechanical and physiological data. Clearly, smart patches are more suitable for monitoring physical activity and health than the other wearable devices presently available [5-7].

Figure 1: A smart patch developed as part of the SINTEC project (left: weight 6.5 g), a smart wristband (centre: 27 g), and a GPS-enabled smart watch (right: 75.8 g).

Unfortunately, the marketing of wearable sensors often involves exaggerated claims with no scientific basis and the data they provide may be relatively or even totally unreliable [8, 9]. Therefore, it is of utmost importance that the validity of any new device of this nature be confirmed prior to widespread usage.

Our primary aim here was to compare the step rate while running in place on a treadmill as measured by the SINTEC smart patch to the corresponding values obtained utilizing the ''gold standard'', which consisted of MEMS accelerometers in combination with bilateral force plates equipped with HBM load cells for running in place and with OptoGait for running on a treadmill. Furthermore, we compared the smart patch data to that provided by the Garmin Dynamics Running Pod, as well as by three-dimensional motion capture with a Qualisys 12 camcorder.

To this end, healthy, physically active volunteers were monitored while running in place on a bilateral force plate (n=15) and on a treadmill (n=14) (Figure 2). On the force plate they performed consecutive 20-second bouts of running in place, starting at low, followed by medium, and finally at high intensity, all self-chosen, while on the treadmill they completed two sessions, each consisting of one-minute runs at 11 and 14 km/h, with a one-min rest between.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Figure 2: Running in place on a bilateral force plate (left) and on a treadmill (right).

Our major finding was that the step rates while running in place provided by all four systems were valid, with the notable exception of the most rapid rate measured by the Garmin Running Pod. The lowest mean bias and limits of agreement at all rates were associated with the smart patch, which in connection with treadmill running also exhibited fair-to-good test-retest reliability. The best test-retest reliabilities were demonstrated by the OptoGait (at 14 km/h) and Running Pod (11 km/h and both speeds combined). Compared to the gold standard, the highest Pearson correlation coefficient and, consequently, the best concurrent validity (at 11 and 14 km/h, as well as both speeds combined) was observed with the smart patch. In future studies, we will examine the validity and reliability of measurements of additional biomechanical and physiological parameters with the SINTEC smart patch.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Highly stretchable and autonomously self-healing conductors for soft electronics

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The idea of autonomously self-healing functional materials for soft electronics is not particularly novel, but their applicability even in academic research has fallen short from the high expectations. The previous attempts of realizing soft, stretchable, and autonomously self-healing electronics have been only partially successful so far. One of the reasons is that even the most simplistic electronic component has multitude of requirements in terms of materials, properties, and structural layout of the component, while additional design considerations must be made in any of the highly deformable electronic devices to enable reliable operation for the long-term.

A considerable technical barrier for the wide applicability has been the limited electro-mechanical performance of the existing self-healing materials made with the traditional polymer-filler particle approach. Several material level trade-offs have been made in terms of tensile, electrical, and self-healing properties which then makes them less ideal for the purpose.

This presentation gives a short background about self-healing materials and overview of the state-of-the-art. The presentation then focuses on discussing the challenges and opportunities, while giving examples, based on the academic research, what kind of material technologies could be possible needed to advance the field.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Gold nanowire-based stretchable conductors for neural interfacing

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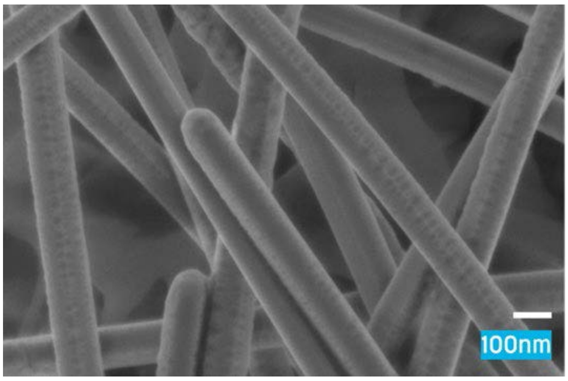
Electrical stimulation in direct proximity to neural tissue is investigated to treat neurological disorders like Parkinson's disease, epilepsy, chronic pain, and paralysis. One major challenge for neural interfaces is the huge mechanical mismatch between the electronics and the tissue. This can be addressed by developing soft and stretchable devices.

High performance stretchable conductors can be made from nanowires embedded in elastomers like polydimethylsiloxane (PDMS). Silver nanowires are commercially available in controlled dimensions and have been widely used for stretchable conductors. For biomedical applications, gold nanowires (AuNWs) are needed, but to date there exists no robust method of synthesizing large amounts of high aspect ratio AuNWs.

In this work we present a novel synthesis of high aspect ratio AuNWs with smooth surface structure and selective control of the diameter of the nanowires. Stretchable conductors based on the AuNW-PDMS composites show high conductivity, low Young's modulus and stable performance under cyclic stretching measurements. The soft conductors were used to develop stretchable multielectrode cuffs with platinum coated AuNWs as electrode material. The cuffs created a conformal and close contact around rat sciatic nerves, which enabled selective functional stimulation.



Well-defined synthesized AuNWs.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Wearable Haptic Display with Dielectric Elastomer Actuators

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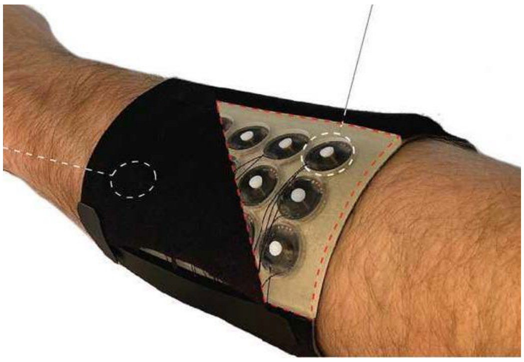
A wearable haptic display communicating with human tactile perception provides a conformal interactive

interface with programmable stimulation patterns. A wearable haptic display transfers meaningful data from networked counterparts or random environments to wearers and communicates. A wearable form enables comfortable and seamless implementations on the human body, and a haptic display enables the programmability of tactile-haptic language with multiple actuators in a mechanical manner. Multiple haptic patterns made of multiple actuation contacts on human skins allow various haptic words and even phrases for more intelligent communication with humans.

To have multiple actuators in a comfortable way of wearing, the compliance and lightweight of haptic display need to be prepared. One of the promising actuators for the requirements is a dielectric elastomer actuator (DEA) that provides compliance and lightweight. Multi-layered DEAs were developed as a compliant and lightweight haptic actuator providing sufficient displacement, force and frequency for haptic stimulation. DEA is electrically controllable at relatively low power consumption and multi-layered DEAs allowed low voltage operation preferable to human applications.

Here, I will present the recent work on wearable haptic displays with dielectric elastomer actuators, realizing a comfortable and lightweight form of haptic sleeves. It made successful mechanical communication with dynamic haptic patterns on human forearms. Human tests showed reasonable responses according to our sleeve design parameters and actuation conditions.



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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Smart wearable systems

[1] Stuart, S.A.E., [1] Panditha V.K.P., [1] Dassen, M.P.A., [1] van de Peppel, R.J.E., [1] Saalmink, M., [1] van der Waal, A., [1] Soundararajan, A., [1] Uzunbajakava, N.E. & [1]* Kjellander, B.K.C.

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Prioritizing health and well-being is one of the sustainable development goals defined by WHO [1]. A study has predicted that better health will add $12 trillion to the global GDP in 2024 [2]. Translated to economic return; for every dollar invested in better health, the gain is double to quadruple. Real-time monitoring of bio-signals with wearables as smart watches connected to smartphones has led the way for remote health monitoring. The use of such wearables and of smart patches, -clothing and -skins are seen as key technology enablers for innovations in health care [2], especially for remote patient monitoring. It is known that the combination and interplay of several sensors, within a multimodal approach would offer a more complete understanding of the human health status. Continuous assessing the vital signs, we get a more complete picture of the health and can detect early signs of infection and identify medical problem. Still, most commercial wearables can only monitor one or a few bio-signals. The body is, however, complex, and it is essential to monitor several signals at different body locations simultaneously.

Accomplishing a wearable to measure high quality medical data the sensors must be accurately positioned at desired places on the body. Taking the ECG as example: the characteristic PQRST wave visualizes the measurement of electrical signal for depolarization and repolarization of the heart muscle which correlates to heart function. Obtaining clinical standard ECG signal quality is a current challenge for medical wearables. Although advancements in electrodes, wearables, algorithms and general miniaturization and material understanding of electrical systems [3] has provided the possibility for real-time biosensor read-out within a more practical form factor. Still, the aspect of obtaining ECG from a single lead design, introduces the impact motion artifact has on the resolution of the ECG signal. Slight alterations in electrode contact with skin, impact of muscle movement and noise within the wearable circuity play a major role in reducing significance in data and resolution obtained of ECG signal. Therefore, a smart wearable system needs to provide a robust skin-contact that is stable and constant in time, even for multiple days. Today's golden standard ECG sensor has an ionic hydrogel component which provides a gradient between the electrolytes within the body with the electrode active area of the sensor which overcomes the skin impedance. Although an imperative component for providing reliable ECG signal, due to the wet hydrogel component, the lifetime for use is limited to a short timespan (24 to 72 hours) as the hydrogel material will dry out and cannot be worn during daily activities such as showering. Research and development within dry electrode technology have provided answers to overcome current electrode problems [4-6]. Dry electrode technology thus has been developed within multiple design directions to overcome this issue and provide a more wearable form factor for a wider use case platform.

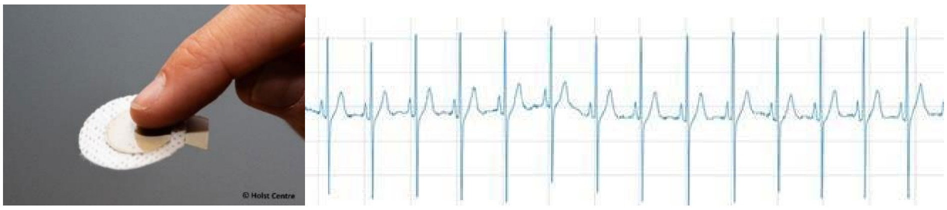

Figure 1. Novel adhesive dry electrode materials for skin-contact ECG sensors (left) and a typical raw-data ECG signal (right).

Figure 2. Printed circuitries on stretchable substrates (left) in mechanical testing equipment evaluating the influence by strain on the conductivity when laminated onto fabrics (centre) and finalized as patch (right).

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For long term wear applications of wearables, it is important that the sensor system is not harming or damaging the skin or limiting one's physical activities. Since the positioning of the skin-electrodes are responsible for the quality of the obtained signal, a solution often used for medical grade monitoring is health patches, that is plasters with embedded ECG sensors glued to the skin. The use of a higher tack adhesive would appear the most lucrative, but this needs to be in combination with other functionalities from breathability to peel strength during removal. If not correctly selected for the specific user group such as for older more fragile skin to locations where skin is more sensitive, the results can have detrimental impact on the initial use of the wearable medical device [7].

Sensors are connected to a conductive circuitry that transmits the measured bio-signals to a communication port (wireless or cabled) or data storage memory. For wear comfort the circuitry needs to be flexible, stretchable, and conformable to the body contours. Such circuitry can be obtained by blending conductive fillers into elastomeric matrices. It is known that repetitive and or extreme strain can cause fatigue and cracks of electrical conductors resulting in decreased conductivity or even failure [8]. Understanding the fundamental impact of strain on the conductivity, the circuitry can be designed in shapes to allow the required stretchability of the wearable to provide robust bio-signal data collection [9]. In a stepwise approach, we evaluate the failure modes and resistance impact during strain load of printed conductive lines, using experimental designed lab-equipment as shown in Figure 2, to extract parameters for designing robust patches.

In this talk we will discuss the potential and challenges for the development of smart wearables systems for bio-signal monitoring. Broadening the sensing capabilities by introducing additional sensors besides the dry electrodes, such as optical and ultrasound sensing systems for patches, we can also address additional analysis capabilities such as chemical composition analysis of blood and in-body imaging. Especially following parameters will be take into consideration during the discussions:

- High quality medical grade data
- Long term monitoring (towards multiple weeks)
- Comfort and compliance
- Modularity and monitoring of multiple physiological biomarkers

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Mechanically Adaptive Mixed Ionic-Electronic Conductors based on a Polar Polythiophene Reinforced with Cellulose Nanofibrils

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Nanocomposite organic mixed ionic-electronic conducting (OMIEC) materials based on soft polythiophene with oligoether side chains with carboxymethylated cellulose nanofibrils (CNFs) as reinforcement agent display mechanically adaptive behavior. Dry films have a Young's modulus of more than 400 MPa which is reversibly decreased to 10 MPa or less upon water uptake. This shows a desirable behavior of a material that initially needs to be rigid to facilitate e.g. insertion into a biological tissue followed by softening upon implantation.

CNFs are found to be a suitable reinforcement agent for soft polythiophene with oligoether side chains which facilitate co-processing of the two materials. Upon addition of 20 vol% CNF the volumetric capacitance is increased from 164 to 197 F cm-3, without overly affecting ionic or electronic mobility. As a result, organic electrochemical transistors (OECTs) feature a transconductance that is independent on the CNF content up to at least 20 vol% CNF. In combination with reversible passive swelling this may facilitate future design of mechanically adaptive OMIEC materials for wearable electronics and bioelectronics.

Keywords: cellulose nanofibrils (CNF), organic mixed ionic-electronic conductors (OMIEC), conjugated polymer, organic electrochemical transistor (OECT), chemical doping.

NeAdEx: Towards Adaptive Telerehabilitation Using Wearable Technology

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With the development of advanced wireless technology, telemedicine applications have rapidly grown under their versatility, portability, and accessibility. Indeed, telemedicine allows patients living in remote areas to benefit from continuity of care while significantly reducing healthcare costs, compared to conventional inpatient and outpatient care [1].

Furthermore, in the wake of the COVID-19 pandemic, patient-support facilities, diagnostic procedures, and follow-up protocols are being converted into remote solutions, making extensive use of technological aids of various kinds. Remote protocols mainly involve contact between the care-provider and the patient via a device and/or envisage replacing or complementing the in-person health assessment with alternative measures, to be carried out at home or in the outpatient clinic. In Telemedicine, user engagement is regarded as a facilitator, as it likely translates into continuity of use [2]. This fosters, for instance, effective follow-up procedures and the probability of success of the rehabilitation protocol.

In the management of neurodegenerative diseases, several attempts to implement e-Health platforms for motor and cognitive assessment and rehabilitation have been made [3][4]. Among those, an approach of increasing interest consists in the use of serious games (or “exergames”) to gamify traditional rehabilitation exercises and assessment protocols. In this scenario, the development of next generation exergames, able to automatically tune themselves according to the level of engagement and mental effort required from the subject, is crucial. Indeed, the complexity of the required task could be reduced or increased depending on the subject’s conditions. To implement this concept, it is necessary to gather information on the physical and mental state of the subject, in a simple and unobtrusive, yet reliable way. A potential application may be monitoring attentiveness and responsiveness through electroencephalography (EEG) to optimise the design and customisation of telerehabilitation protocols.

However, to date there is a lack of a stable, reliable, and minimally invasive framework to assess user engagement based on physiological parameters, both in healthy and pathological subjects. NeAdEx (NeuroAdaptive Exergame) is a research project aiming at developing a platform for adaptive telerehabilitation through exergaming. The adaptation concept focuses on exploiting commercial wearable devices to collect various physiological data, which are then linked to the subjects’ physical and emotional state during gameplay.

A pilot study was conducted involving 50 healthy volunteers, to assess the feasibility of the instrumentation and the designed protocol in assessing user-engagement. The experimental protocol consisted in playing a customised exergame (with 4-levels of increasing difficulty) mirroring upper limbs rehabilitation exercises, such as the hand grasp and drag-and-drop movements. Several stressors were introduced at each game level, likely to elicit an increase in the level of engagement and/or stress in the subject playing the exergame. Figure 1 displays the game scenario in one of the designed levels.

Figure 1. Game scenario at Level 4 of the exergame. The user hand is mirrored on screen.

The employed physiological signals were collected using the following devices: a wearable electroencephalography (EEG) headset (single-channel analysis), the Empatica E4 wristband for electrodermal activity (EDA) and heart rate variability (HRV), and an RGB camera for video-recordings for the eye-blink detection.

"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Offline analysis was conducted on the collected biosignals, through signal processing and Machine Learning (ML) techniques. Descriptive features of the brain activity (EEG morphology and regularity parameters), eyeblink (frequency and duration of the blinking), EDA (morphology and frequency parameters) were extracted for each game level [5]. The features were used in supervised ML paradigms (Support Vector Machine, KNearest Neighbour, AdaBoost) to automatically detect the different levels of engagement elicited by the specific stressors in the game levels.

From the combined analysis of EEG and Eye-Blink features, the tested ML models attained an overall accuracy over 90% (REST condition vs GAME classification), with F-1 scores exceeding 90%. A further classification between the Low-Engagement and High-Engagement game-levels was performed, achieving a maximum of 72.2% overall accuracy, with an alike F-1 score. Based on these promising results, the 4-stage classification (i.e., specific recognition of each of the four game levels) was attempted. However, the averaged classification performance faced a slight decrease, and, even after a thorough feature selection process, it did not attain as satisfactory scores as the binary classification ones. This suggests that the implemented models, based solely on EEG and eye-blink parameters, could not effectively discriminate the four game levels.

On the other hand, the sole analysis of the EDA collected in the four different levels proved much more efficient in the recognition of each game level, therefore filling this gap, with the best model scoring an overall accuracy of 93%. The scatter plot in Figure 2 displays the efficiency of the EDA parameters in discriminating the four game levels.

The obtained performance demonstrates the capability of the designed framework in detecting attention and engagement states during Telerehabilitation exercises, by means of low-cost and minimally invasive wearable technology. These results pave the way to the following two e-Health scenarios. First, the application of the exergame in motor and cognitive rehabilitation for people with Parkinson's Disease (PD). Indeed, rehabilitation protocols should be tailored on the single specific subject to optimise the expected results. Nevertheless, the effectiveness of this framework on pathological subjects, and the ability of the system to tune real-time are still under investigation.

A second scenario involves people with obesity, in which the exergame could be used to detect stress and stress-related physiological responses. The game could also play a role in rehabilitation, as a tool for improving their capability of coping with stressing situations, which is also known to have a direct link with eating disorders.

To achieve both these directions, future developments will include the evaluation of multimodal features, i.e., a combined analysis of EEG, eye-blink parameters, HRV and EDA, to maximise the accuracy of the model and enhance its robustness and generalisation capability. Experimental data collections and preliminary work to this end are currently underway.

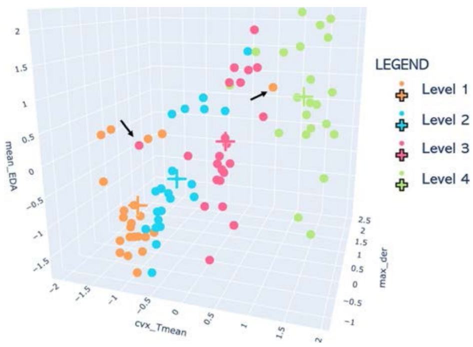

Figure 2. Scatter plot of the three most relevant EDA features in the four-level classification task.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Oral presentations
28th April 2023

ABSTRACTS

Sustainable, digital production of wearable soft-stretchable electronic devices

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The production and consumption of electrical and electronic equipment (EEE) in the European Union (EU) are on the rise (Eurostat 2020). Due to low levels of reuse, collection, recycling, and other forms of recovery of waste EEE, the consumption of rare and expensive natural resources is also increasing. This imposes higher economic and environmental pressure on manufacturers of modern electronic devices. As new fields of applications for stretchable electronics continue to emerge, such as wearable smart textiles and medical/health-monitoring devices, the market for stretchable electronics is expected to grow rapidly. Amid the COVID-19 crisis, research indicates that the global stretchable electronics market will reach $2.6 billion by 2027 (Researchandmarkets 2020).

The development of methods to assess the ecological impact of not only the electronic device, but also the production process, is an area of research that is growing. Life Cycle Assessment (LCA) is a useful method to identify and quantify the environmental impacts of a product, process, or activity. Comparative LCA can be carried to compare the environmental impacts of two or more products that have similar functionality.

The production process for stretchable electronics that is being developed in the SINTEC project is based on a digital production strategy, where the production steps are digitally controlled and optimised. An example of a proposed production line, including deposition machines, inspection devices et cetera, is shown in Figure 1. A comparative life cycle assessment of stretchable and rigid electronics-based cardiac monitoring devices will be discussed to elucidate aspects of the production process from an environmental point of view.

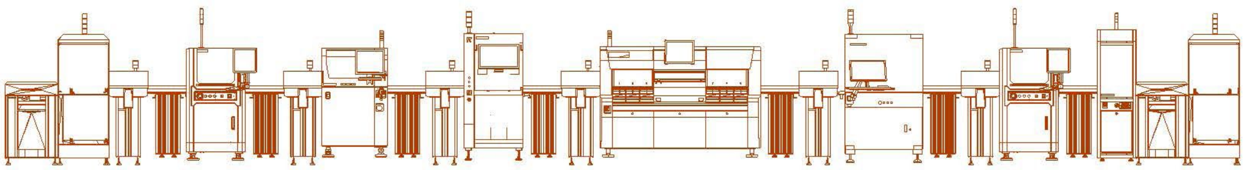

Figure 1 : An example of a digital printing line, including modules dispensing, coating, and inspection, for the production of wearable, soft, and stretchable physiological monitoring devices.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Chemical and Electrochemical Doping of Conjugated Polymers and Correlation between Electrical and Mechanical Properties

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Chemical and electrochemical doping are widely used to modulate the electrical properties of conjugated polymers. Doping of thin films facilitates fundamental spectroscopic studies and, ultimately, is important for the operation of devices from transistors to solar cells. However, some applications such as thermoelectrics and wearable electronics require bulk materials, which complicates doping processes. This talk will explore some of the fundamentals of doping of both thin films and bulk materials. The impact of doping on the electrical as well as mechanical properties will be discussed, and it is shown how doping can be used to tune both the conductivity and stiffness of conjugated polymers. Finally, strategies are explored that permit to decouple the effect of doping on the electrical and mechanical properties, which can be used to prepare a variety conducting bulk materials, from stiff foams to stretchable fibers.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

An Innovative Portable Gateway for IoT-Sensors in Rehabilitation and Sports

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In this age with aging populations all over the world, many countries face the challenge of increasing healthcare expenses. To overcome this problem, the internet of Things will be one of the key technologies. The problem of uncomfortable rigid sensors is overcome in the SINTEC project by using soft and flexible sensor patches. To connect these sensor-patches to the cloud a infrastructure was developed consisting of a secure wireless gateway, BACE Go, and a cloud environment, the FIWARE cloud. BACE Go permits data gathering from the SINTEC sensors from the test subjects in clinical as well as in athletic environments. We will demonstrate the power versatility and robustness of this new device and the corresponding on-body network. This will ultimately lead to better patient care and reduced healthcare costs.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Photoinduced Polymerization of Small Molecules for the Formation of Organic Electronic Devices

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The application of small self-organized molecular systems for the formation of soft and in situ electrodes with combined electrical and biochemical signals leads to new means of bridging the biology-technology gap. Such systems have seen increased attention over the past few years with their promise of entirely novel pathways for monitoring and augmenting biological function [1]. In parallel, organic electrochemical transistors (OECTs) have become a standard tool in the field of organic bioelectronics as they can take full advantage of ion (biomolecule) injection from an electrolyte (or physiological system) to modulate the volumetric conductivity of an organic semiconductor channel [2]. In addition, overall biocompatibility and synthetic tunability of the organic conductive polymers make OECTs ideal for interfacing with biological systems.

In this work we have combined the burgeoning field of in situ formed organic electronic materials into an OECT platform by using light-assisted photocatalysis. Specifically, we used direct light excitation, as well as excitation of porphyrins, for the in situ photoinduced polymerization of conjugated oligomers. The conjugated oligomers, bis[3,4ethylenedioxythiophene]3thiophene sulfonic acid (ETE-S, i.e., an EDOTthiophene- EDOT trimer with a sulfonate ligand) and a variety of derivatives (ETE-CooNa and EEE-CooNa) were implemented, and the photoinduced polymer films were assessed by cyclic voltammetry as well as transistor output and transfer characteristics. The resulting OECTs exhibited excellent figures of merit (transconductance, on/off ratio) with performance approaching PEDOT:PSS but with several advantages. We believe that these results pave the way for expanded in situ bioelectronics and even OECTs and similar component fully formed/fabricated in vivo.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Materials and Methods for Sustainable Soft Devices - From Biodegradable Tough Gels to Mycelium Based Elektronik Skins

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Modern societies rely on a multitude of electronic and robotic systems, with emerging stretchable and soft devices enabling ever closer human machine interactions. These advances however take their toll on our ecosystem, with high energy demand, greenhouse gas emission and environmental pollution.

Mitigating some of these adverse effects, this talk introduces materials and methods for soft systems that biodegrade. Based on highly stretchable biogels and degradable elastomers, our forms of soft electronics and robots are designed for prolonged operation in ambient conditions without fatigue, but fully degrade after use through biological triggers. Electronic skins provide sensory feedback. Enabling autonomous operation, stretchable and biodegradable batteries are demonstrated that power wearable sweat sensors. 3D printing of biodegradable hydrogels enables omnidirectional soft robots with multifaceted optical sensing abilities. Going beyond, we introduce a systematically-determined compatible materials systems for the creation of fully biodegradable, high-performance electrohydraulic soft actuators. These embodiments reliably operate up to high electric fields, show performance comparable to non-biodegradable counterparts, and survive over 100,000 actuation cycles. Pushing the boundaries of sustainable electronics, we demonstrate a concept for growth and processing of fungal mycelium skins as biodegradable substrate material. Mycelium-based batteries with capacities as high as ~3.8 mAh cm−2 allow to power autonomous sensing devices including a Bluetooth module and humidity and proximity sensors, all integrated onto mycelium circuit boards.

"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Multimodular small and low-power sensor boards for smart patches

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In recent years the wearable market has grown significantly. Especially during the pandemic period, the importance to monitor the most important vital parameters deeply and in a simple way was crucial to better address the therapies in a more effective way. Parameters like SPO2 and Heart Rate became commonly discussed not only by professionals but also by ordinary people.

Simplifying the access to the vital signs monitoring can enlarge the screening base, help the operators to develop most robust solutions to a specific problem, and can cut the associated cost, reducing the necessity to go directly to the hospital or to use complex and expensive instruments.

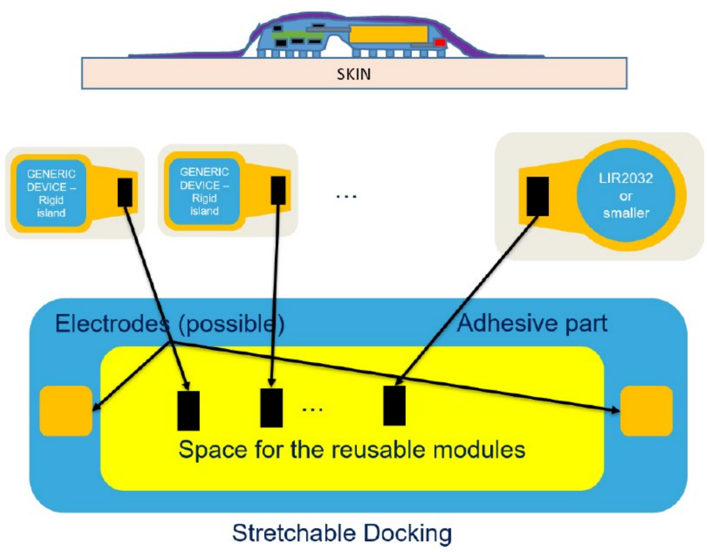
The innovation in electronical components reduces the cost and the dimensions of the integrated circuits enabling down scaling of dimensions and costs while increasing the number of functions available. This will simplify the clinical exams, keeping unvaried the performances.

We present here a novel hardware architecture designed and developed in the EU-funded SINTEC project which can provide a good solution to the issues listed above. The targets of this work were multiple. First to develop new sensors capable of performing complex clinical exams in a simple manner using integrated circuits not originally designed for medical purposes. Second to develop sensors usable by ordinary, often elder, people. Lastly, to consider the environmental impact of the device by developing systems with reusable parts to reduce electronic waste.

The system presented has parts dedicated to the conditioning and acquisition of vital signs, while others focus on the elaboration of the data, and finally others to store and send the data. Obviously, all these parts have been designed to guarantee proper performances, while still reducing power consumption and dimension.

New methodologies for the data extraction have been coupled to new algorithms, often based on neural networks and machine learning, capable of computing different parameters correctly while keeping the footprint of the complexity limited.

The system has a novel architecture that is readily adaptable which ensure a large range of uses, focusing on flexibility and comfort.



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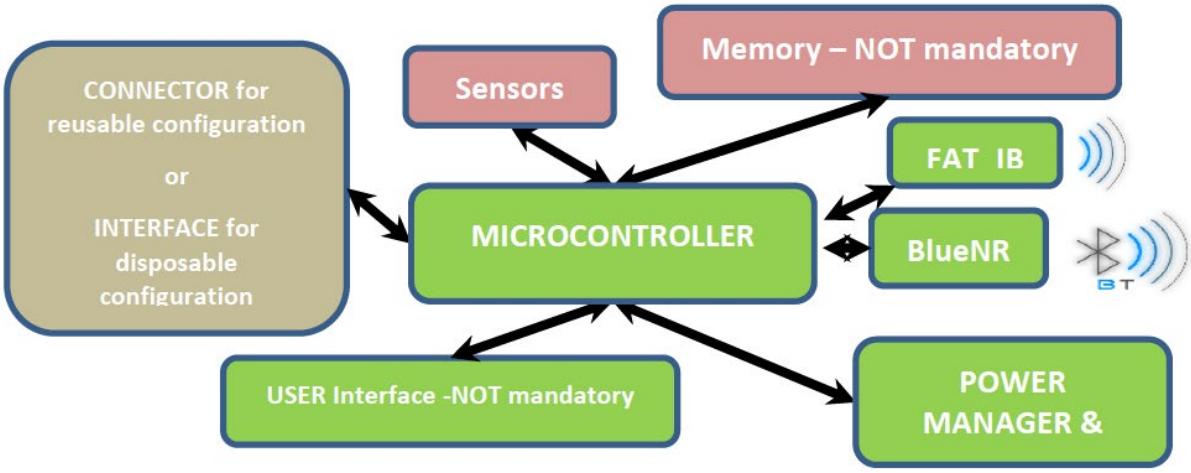
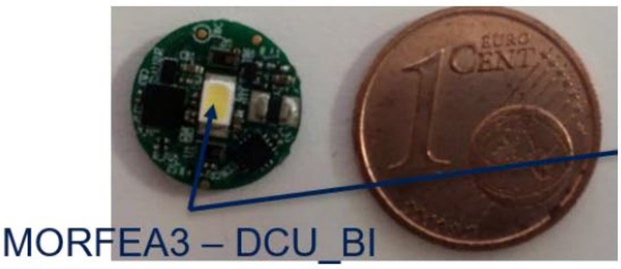
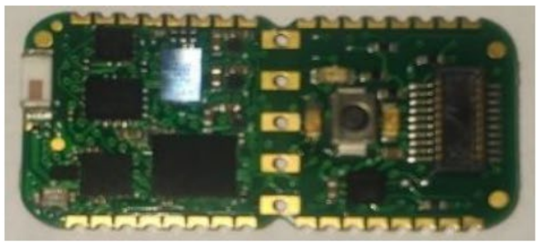
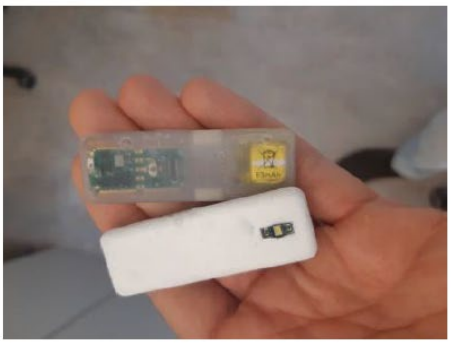
This architecture can be divided in two different groups of components: disposable parts and reusable parts. The disposable parts are innovative electronic stretchable patches developed by Uppsala University. The patches connect to and protect the electronics while assuring a good contact with the skin of the user. The cost of the stretchable patches is restrained and its technologies has been previously presented [1]. The reusable parts, on the contrary, are more expensive since they contain all the integrated circuits mounted on a tiny multi-layered PCB and the battery.

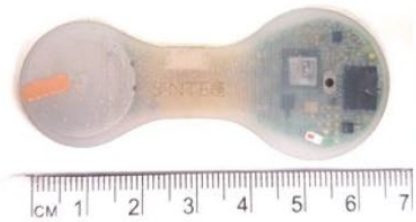


Their reusability ensures a long life and a low impact on the environment. Here, we report the boards realized in the project with a general block diagram.









These boards cover a wide range of possible clinical exams and they have been designed to be very small to minimize impact on the usability of the system. They have a standardized output and behaviour in order to be used and changed inside the architecture cited before. These boards use standard integrated circuits not originally designed for medical applications. This approach opens up for devices with lower power consumption as well as a lower over-all cost. The features of these boards and modules have been demonstrated and are now in a clinical and sportsperformance validation phase.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Monitoring Sleep Patterns in Parkinson's Disease through Inertial Measurements

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The investigation of sleep disorders (SD) is increasingly gaining attention in research, also due to their role in the development of neurodegenerative diseases. Indeed, SD are listed among the earliest prodromes of alpha-synucleinopathies such as Parkinson's Disease (PD), with REM Sleep Behaviour Disorder featuring a 90% conversion rate at a 14-year follow-up [1].

PD is the second-most common neurodegenerative disorder; the aetiology is still unclear, and at present there is no curative therapy. Nowadays, symptomatic treatment aims at mitigating the motor manifestations, with the support of physical rehabilitation. However, reaching an optimal approach to treatment is challenging, given the unpredictable nature of the disease, as well as the diversity in its symptomatic manifestation.

PD motor symptomatology usually involves reduced mobility, muscle stiffness, bradykinesia, and tremor. However, also non-motor symptoms (NMS) are highly preponderant in PD; these include autonomic disorders, cognitive impairment, behavioural symptoms such as depression, speech alterations and sleep dysfunctions. These latter are acknowledged as the most common NMS, with a prevalence up to 90%. Among these, nocturnal hypokinesia – i.e., reduced motility during the night – and akinesia affect up to 50% of the subjects already in the earliest stages of the disease.

Nowadays, a major issue in the management of PD lies in the fact that neurological assessments are infrequent (6- to 12-month basis), costly, invasive, and time-consuming. In addition, clinical evaluation mainly relies on subjective metrics or self-reported questionnaires. Therefore, there is a need to monitor the subjects' health and their symptoms fluctuations by means of objective parameters, possibly through lightweight and continuous solutions.

Regarding sleep studies, the state-of-the-art is polysomnography, a complex examination which involves a high number of electrodes. A smoother solution is provided by actigraphy, which monitors overnight motility through inertial sensors. However, the devices are usually placed on the less dominant wrist, therefore carrying little information about whole-body and trunk movements. This work presents a lightweight framework for monitoring overnight motility and sleep quality (SQ), through a Shimmer3 inertial measurement unit (IMU) placed on the chest during sleep.

The experimental protocol involved 32 subjects (24 healthy controls, HC, 8 PD patients, PDP). All participants filled out the the short Pittsburgh Sleep Quality Index (sPSQI) questionnaire – commonly employed in the clinical practice to evaluate sleep quality through self-reported measures [2] – and a second questionnaire, specifically designed to investigate life habits related to circadian rhythms [3].

Motility data collected through the IMU included data from a triaxial accelerometer, gyroscope, and magnetometer, respectively (Figure 1); for future analysis, also vocal recordings were collected, through a smartphone. The inertial signals were pre-processed for background noise removal, and features describing overnight motility were extracted. Given the aim of the study, i.e., characterise overnight motility in PD and create objective measures, the extracted parameters accounted for the number of turns in bed, the turning velocity (related to nocturnal hypokinesia and bradykinesia), the duration of each turn, and the activity index. This latter is based on the variability of motion, and accounts for the overall night motility over the three axes.

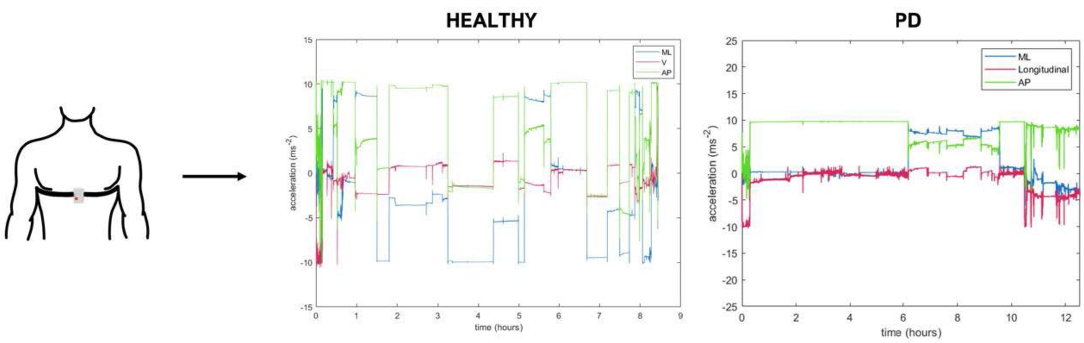

Figure 1. IMU positioning and accelerometer data during sleep, for a healthy and a Parkinson's Disease subject, respectively.

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First, a statistical analysis was performed on the extracted parameters, through the U-Mann Whitney nonparametric test, to assess the presence of statistically significant differences between HC and PDP, and between Good and Bad Sleepers. Moreover, with the aim of evaluating a possible influence of the disease on the assessment of SQ, two additional tests were carried out, between: (i) HC with good SQ versus HC with bad SQ; (ii) HC with bad SQ versus PDP with bad SQ. It is worth noting that no comparison was made between HC with good sleep quality versus PDP with good sleep quality, due to the limited numerosity of the latter subset. In addition, the Spearman correlation coefficient was computed to assess the presence of a correlation between the sleep features and the sPSQI, which is the clinical indicator of sleep quality.

According to our findings, several features tested their effectiveness in discriminating between HC and PD patients. Among these, the parameters that showed the most significant differences included the tilt angle in bed (p-valueHC vs PD <0.001, p-value HCBAD vs PDBAD = 0.004), the angular velocity of turns (p-valueHC vs PD <0.001, p-value HCBAD vs PDBAD <0.001), the activity index (p-valueHC vs PD <0.001, p-value HCBAD vs PDBAD <0.001). As appreciable from the reported level of significancy, the features resulted to be highly representative of the disease and minimally influenced by the quality of sleep. As for the analysis between Good and Bad sleepers in the HC subgroup, the results revealed the standard deviation and skewness of the duration of turns as statistically significant (p-value=0.03 and p-value=0.002, respectively). Among these, the former also revealed a significant correlation with the sPSQI score (r=-0.43, p-value=0.0038). From the feature selection process, the relevant features are all related to trunk movements; this further confirms that motility features, in the case of PD monitoring, should be recorded at the chest, instead of the classical positioning provided by consumer-grade wearable devices.

The second step involved a Machine Learning (ML) classification approach to automatically identify subjects based either on the presence of PD, or on the quality of sleep. The pipeline of the employed model included: (i) z-score normalization step to prevent outliers from excessively influence the performance, (ii) a feature selection method based on a correlation approach [3] to select a set of the most discriminative features, (iii) a Support Vector Machine (SVM) classification algorithm. The classification performance was evaluated by means of a Leave One Subject Out (LOSO) approach. The models yielded a 96% accuracy in detecting PD (0.93 F-1 score), and a 78% accuracy in identifying good versus bad SQ (0.72 F-1 score).

The results attained by the ML algorithm proved the efficiency of the selected parameters in discriminating PDP from HC, based on overnight motion patterns recorder through wearable sensors. This would allow for minimally invasive sleep studies, to be performed also at home, as well as continuous monitoring solutions, bridging the gap between outpatient scheduled assessments. Furthermore, the proposed framework proved the feasibility of assessing sleep patterns in PD through a set of objective metrics, which could facilitate monitoring the disease progression over time. Future work should address a larger PD population, with different disease progression levels, to ensure better generalisation capability of the tested models. Given the promising results yielded by this feasibility study, the next experimental sessions will include the quantitative analysis of electromyographic (EMG) recordings during sleep, as proposed in [4], which would add significant information about muscle activation patterns. Finally, as vocal dysfunctions have also been linked to sleep disturbances [3], vocal recordings have been collected from the participants, and will be included in the next analysis. This will provide a multi-modal (inertial, EMG and vocal-based), lightweight approach for the evaluation of both motor and NMS fluctuations in PD, allowing for objective monitoring of the disease progression and personalised treatment, likely improving the quality of life of patients.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Validity of the CORE sensor to assess core body temperature during cycling

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High ambient temperatures and associated thermal strain is a common challenge for athletes competing in summer sports. The environmental conditions during the Olympic Games in Tokyo ranged from 29 to 33°C and 70 to 80% relative humidity. Next Olympic games will be held in Paris where during the heat wave temperatures can go above 40°C. Hot, humid climates limit the body's ability to transfer this heat to the environment. The challenge of maintaining thermal homeostasis is intensified by endogenous heat production by working muscle during exercise. Consequently, core temperature (Tc) becomes elevated above the resting level of 37°C. Exercise in these conditions may be accompanied by adverse psycho-physiological responses and heat illness.

Monitoring Tc during exercise is therefore an important part of the training process in order to achieve the desired stimuli or adaptation to a particular training session and to avoid heat-related medical problems. It is therefore of utmost importance to provide athletes and coaches with a valid, reliable, and easy-to-use strategy for monitoring Tc.

In recent decades, ingestible temperature sensors (pills) have become a popular alternative for research and professional sports. Several studies have shown that pills are suitable sensors for measuring body temperature [1,2,3]. However, this technique also has some limitations, including the fact that the pill must be taken several hours before exercise, it can be contaminated by ingestion of food or fluid, and it is also expensive. Therefore, monitoring Tc levels during each training session or competition with ingestible pills is not widely used.

Therefore, a potential noninvasive sensor that allows monitoring of Tc during each training session or competition would provide significant benefits in terms of heat acclimatisation or acclimatisation training and prevent the occurrence of heat stroke. A noninvasive sensor that allows accurate monitoring of Tc during specific time periods would be of great benefit not only to athletes, but also to workers exposed to high thermal stress (e.g., firefighters and soldiers), as well as for obtaining important diagnostic information in the clinical setting [4]. Recently, one such sensor, the CORE (greenTEG AG, Rümlang, Switzerland), has become commercially available (Figure 1) [5]. The aim of this study was to evaluate the validity of CORE sensor with BodyCap e-pill (Saint-Clair, France).

Figure 1. CORE sensor on the participant's chest.

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Ten healthy and physically active male volunteers (age = 30 ± 5 years; body mass = 75.0 ± 8.2 kg; height = 180 ± 5 cm; peak oxygen uptake (VO2peak) = 65 ± 6 mL min−1 kg−1 (means ± standard deviations)) participated in this study, which was approved by the Ethics Committee for sport at the University of Ljubljana, Slovenia, which adheres to the principles outlined by the World Medical Assembly Declaration of Helsinki. Informed consent was obtained from all subjects involved in the study. The subjects included were men younger than 40 years of age who cycled for at least 8 h each week.

Each participant cycled twice for 30 minutes in a heat chamber (35°C, 70% humidity) at 50% of the maximum wattage achieved during a ramp test, Figure 2.

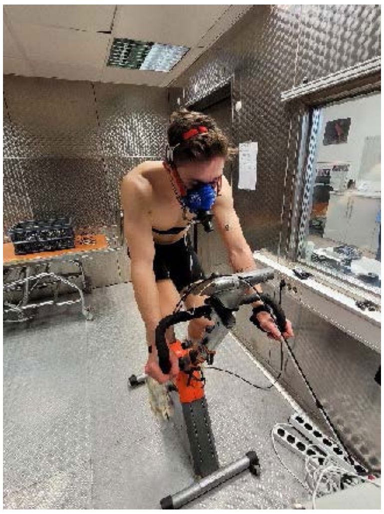

Figure 2. The participant cycling in a heat chamber

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Wearable patient monitoring sensors for intra-hospital use

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This presentation focuses on the unique challenges and requirements of wearable patient monitoring sensors from the viewpoint of a medical electronics manufacturer. I discuss the importance of understanding the medical space realities and the need for collaboration among manufacturers, research, and healthcare sector stakeholders to address sustainability, reduce fragmentation, and ultimately, get adoption at scale. Join me as I delve into the opportunities and challenges in wearable patient monitoring, aiming to optimize hospital workflows, enhance patient care, and steer innovation in the field.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Fat – Intra Body Communication: A new paradigm for intra-body communication technology enabling reinstatement of lost functionalities in human

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Intra body communication has been researched quite extensively for past couple of decades to serve the needs in real time monitoring, drug delivery, sensing for pre-emptive measures and to provide better quality of living to the population. The applications are not just limited to health care but also span the areas of recreation, sports and information technology. A handful of intra body, more specifically human body centric (HBC) communication modalities have been developed so far namely galvanic, capacitive and inductive methods. Human body or part is used as a communication channel in these technologies. Though they offer the possibility to connect devices and transfer data wirelessly from one part of the body to the other they suffer from one common drawback which is the low bandwidth hence lower data rates. Radio frequency communication has been regarded until recently as an improbable candidate for extensive HBC applications. In 2016 the Asan et. al from the Microwaves in Medical Engineering Group, Uppsala University, Sweden published her first paper on the feasibility using the adipose tissue to transmit Microwave signals inside the body with significantly low loss(2dB/cm) [1]. Since then a number of articles have been published on different aspects of fat – intra-body communication (Fat-IBC) [2-6]. Considering the human anatomy the fat tissue is found to be sandwiched between denser tissues such as skin and muscle. As it is known that the fat due to its very low water content has low permittivity and losses while muscle and skin do have almost an order of magnitude high permittivity and losses which is three to four times that of fat. This creates a natural wave guiding structure which we can utilize to transmit microwave signals at ISM frequencies. Fat- IBC pushes further the current limits in intra-body data transfer by providing a higher bandwidth and enabling better power management to ensure longer implanted battery life. Fat channel communication will also help substantially the development of artificial limbs which require transfer of high volume electrophysiological data, wirelessly.

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"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Poster presentations
ABSTRACTS

Ionic transportation in electrospun nanofiber for wearable electronics

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A smart and new class of polymer electrolyte is composite of electroactive polymers and ionic liquids. The electromechanical transduction properties of the electroactive polymer, high ionic conductivity of the ionic liquids and easy preparation of this composite makes them suitable in the fields of energy storage, actuators, tissue engineering with large application potential (1-3). More recently, electrospinning is found to be an innovative technique to prepare different types of polyelectrolyte membranes with improved conductivity (4,5). In this work, ionic liquid and electroactive polymer composite mat is prepared via electrospinning to make a flexible polyelectrolyte membrane. The ionic conductivity is found to be one order higher than the solution casted film of the same composite even when the fibers have a porosity of ~77%. The polarization observed in the fibers of the polymer matrix is thought to be responsible for the notable increase in ionic conductivity, which may be due to the in-situ poling of the electroactive polymer that occurs during the electrospinning process. An organic ionic thermistor (i-thermistor) was fabricated and demonstrated utilizing the improved ionic conductivity of the fibers with negative temperature coefficient (NTC) property. The flexible i-thermistor can successfully map temperature distribution. This smart composite nanofiber is auspicious for diverse application such as thermistors, energy harvesters and wearable electronics as well.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Objective Monitoring Technologies in Spinal Deformities

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Adolescent idiopathic scoliosis(AIS) is a three-dimensional structural deformity of the spine consisting of lateral deviation&bending in the frontal plane, rotation in the transverse plane and disturbance of the sagittal plane normal physiological curves usually result in a flat back [1]. AIS is a structural deformity of the growing spine between the ages of 10-18 and worldwide prevalence is 2-3% [2]. A rigid brace is used in the treatment of moderate curvatures of 20-45 degrees. Brace treatment is aimed to prevent the progression of the deformity and avoid surgical treatment. Scoliosis braces are expected to correct the spinal deformity in the trunk or control/stop its progression by corrective external forces, maintain growth with proper loading, and thus protect the spine from degeneration in adulthood [3]. In order to achieve the best possible correction in a brace, there should be three-point system in the frontal plane, derotation forces in the transverse plane and corrective forces that will create a physiological alignment in the sagittal plane. In order to provide adequate derotation, it may be necessary to use extra pads generating vectorial forces in the ventromedial or dorsolateral direction [4]. Brace treatment stop when skeletal maturity is reached. Corrective forces applied by the brace (and strap tension, extra peds), wearing time, patient compliance, age and bone maturity are the factors affecting the success of the brace treatment[5].

What and why do we monitoring in the treatment?

Nowadays treatment success in AIS is mostly up to clinicians' experience due to the inadequate objective outcome measures to determine the effectiveness of the brace. Currently, the relatively objective only predictor of the success of brace treatment is in-brace radiography since we don't have any other objective measurement regarding applied forces, the elasticity of the tissue, wearing time, and how much force can correct the deformity without creating skin irritation or compensatory curvature due to overcorrection etc. As clinicians our knowledge of brace effectiveness is limited, and we need to develop objective success criteria. In managing the treatment, brace monitoring gains importance to detect adequate wearing time and sufficient pressure that does not cause any treatment-related side effects. Objective measurement methods are required to determine the direction, location and intensity of the forces applied by a brace, treatment dose, wearing time, and compliance for the treatment to be effective [6], [7].

What do we have in the market? What are the current problems?

Pressure sensors and thermosensors were used for monitoring the brace treatment [8], [9]. Thermosensors are a good indicator of wearing time however it does not provide other information regarding the effectiveness of the brace. Another disadvantage if the outdoor temperature exceeds a certain level, it might be insufficient for measurement. Pressure sensors provide some more details however they were not functional outside the laboratory [9]. A potential problem is placing the sensor on the plastic material of the brace. Because in this case, sensors cannot place like in athletes. Additionally, sensor size, weight, and battery duration are not suitable for daily life because patients' brace-wearing time is approximately 20 hours/day for at least for a year.

What do we need? What do we expect?

Clinicians need to understand treatment effects to guide the patients and need to know if their prescription is correct. Clinicians need an answer for when to revise or prescribe the new brace, when to finalize the treatment, and are we overtreating some patients.For this reason following parameters needs to objectively measure:

- compliance
- wearing time
- effectiveness of treatment & tretment success
  - intensity of the corrective forces
  - direction of the corrective forces
  - localization of the corrective forces
  - appropriate design
  - strap tension
  - dose
  - body reaction to the corrective forces
  - material endurance, material-tissue interactions
  - side effect
  - extra pads necessity&location and size of the pads

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

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"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Low Power Biopotentials Acquisition Using MEMS and Charge Transfer for Wearable Applications

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The aim of this work is to use an extremely low power MEMS electrostatic sensor based on charge transfer, the ST Qvar, for biopotentials recording in wearable applications. Here, we report about the acquisition of Electroencephalography (EEG), Electrooculography (EOG), Electrocardiography (ECG), and validate data by comparison with certified medical gold standards. (Surface Electromyography (sEMG) through Qvar has been also demonstrated and is currently under validation).

To the aim, the Qvar has been provided with a dedicated analog preamplification circuit and has been connected to an ARM M0 MCU (microcontroller unit) that handles data collection and sends it to an external software for processing.

At the cost of additional 15 mA per sensor, plus 150 mA for the pre-amplifier, the ST Qvar enriches the MEMS capabilities by enabling the acquisition of biopotentials.

This opens to long-term recordings, increasingly needed for better diagnoses of many pathologies (like atrial fibrillation), and to the on board-implementation of complex algorithms (as Artificial Intelligence), not possible on already power-hungry systems. Furthermore, it represents a excellent use case where the stretchable architecture developed in EU-funded SINTEC project can be applied.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Robots - Implants - Sport Performance : Applications of Miniaturized Systems with Soft Materials

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Soft materials give comfort and can gently comply with a body. By introducing such materials in new application domains the recent decade, this has created two technology revolutions:

(1) In soft and stretchable microsystems for decentralized personal health monitoring of biometrics in sports, healthcare, and in everyday life.

(2) In soft robotics, for applications in, e.g., logistic of soft and fragile materials, medicine and humanoids.

The Microsystems technology (MST) program at The Ångström Laboratory pioneered soft and stretchable printed circuit board technology with liquid metal circuitry and has been forwarding its use with an increased maturity. In addition, it has recently started to use textile technology for robotic textiles. In the poster, the technologies are presented with applications in microrobots for intelligent agriculture, textile robots for haptics, and soft electronics for cochlear implants, remote patient monitoring and sport performance.

MST is working close to hospitals and industrial partners and in the projects presented, our stakeholders are Uppsala and Linköping Academic Hospitals, STMicroelectronics, Evalan, Mysphera, Atlas Copco, Volvo Cars, Sandvik, and especially Mycronic.

I acknowledge funding from the European Union's Horizon 2020 research and innovation program under grant agreements No 824984 and No 101016411, from the Swedish Research Council under grant agreement 2017-03801, and from the Swedish Foundation of Strategic Research under grant agreement CHI19-0034.

Printed Bioelectronics via In-Situ Enzymatic Polymerization of Conjugated Oligomer-based Hydrogel Bioinks

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Hydrogels are an attractive material system for interfacing between medical devices and human neural tissues due to their similar mechanical properties. However, most conventional hydrogel-based bio-interfaces lack electrical conductivity and thereby cannot relay electrical signals related to neural recording and activation. Here we show how in situ enzymatic polymerization of the conjugated oligomer-based hydrogel can be utilized to create cell-compatible and electrically conductive hydrogel structures. Conductive hydrogel structures were fabricated using 3D printing of hydrogel bioinks loaded with conjugated oligomers, followed by enzymatic polymerization of the conjugated oligomers by horseradish peroxidase. The polymerization of the conjugated oligomers modified the electroactivity of the hydrogels and resulted in a significant increase in stiffness from about 0.6 kPa to 1.5 kPa. Both the components and polymerization process as well as the resulting conductive hydrogels were well tolerated by both human primary fibroblasts and PC12 cells. This work thus shows possibilities to fabricate cytocompatibility and conductive hydrogels that can be processed using bioprinting. In addition, these hybrid materials show tissue-like mechanical properties, and the hydrogels possess mixed ionic and electronic conductivity, which can provide new means to leverage electricity to manipulate cell behavior in a native-like microenvironment.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Digital manufacturing of soft, stretchable and wireless sensor patches with liquid metal interconnects

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In the recent past, the development of soft and stretchable wireless sensor patches has invigorated the field of wearable technology, and these devices and methods have the potential to revolutionize how we monitor and track physiological signals. In order to reliably record signals, such as heart rate, respiratory rate, skin temperature, etc., the devices should be made from sufficiently flexible, elastic and soft materials that conform to the contours and shapes of the body and allow for comfortable and non-invasive monitoring. These requirements also apply to the electronic circuits of wearable devices, where characteristics of high electrical conductivity, high strain tolerance and resistance to fatigue are vital. Gallium-based liquid metal alloys offer a unique combination of these characteristics making them excellent alternatives to conventional conductive, stretchable inks. To enable these promising devices, effective automation solutions for the production of digitally printed circuits remain a challenge for the electronics industry. With the aim to industrialize a soft and stretchable printed circuit board technology, we present a manufacturing strategy that utilizes digital surface mount technology from contemporary assembly lines. A needle dispensing technique was adopted for the precise and digitally programmable patterning of liquid metal alloy conductors. We investigated and mapped conditions of reliable printing for two sizes of dispensing needles (inner diameter of 150 μm and 360 μm) performed on 15 μm thin medical polyurethane film, enabling patterning of traces ranging from 70 to 275 μm in width. In order to provide adaptability, as well as overall robustness of the device, the strategy further included the integration of flexible printed wire board interfacing rigid components and liquid metal conductors or used as a flat cable connector to computing electronics, see Figure 1. An array of the circuitry with embedded electrodes for electrophysiological readout was patterned over a large area (A4 size) on various elastomeric substrates, such as polyurethane or silicone, which was subsequently laminated onto elastic sports or medical tapes. The presented sensor patch is modular. Functional rigid electronic components, i.e. sensor boards and power supply, are integrated into a multiuse module, which can significantly reduce the number of expensive electronics to be disposed of after use. The thin silicone-embedded wireless module is coupled to and covered by a single-use, disposable skin-adhesive patch that ensures adhesion to the wearer's skin and protects the module under moving clothes. Aspects that concern comfort and unobtrusiveness while wearing the patch were taken into consideration. The reliability of wireless connection, data acquisition and transmission were verified. The manufactured soft and stretchable sensor patch exhibits the ability to monitor electrocardiography and wirelessly stream the signal in real-time.

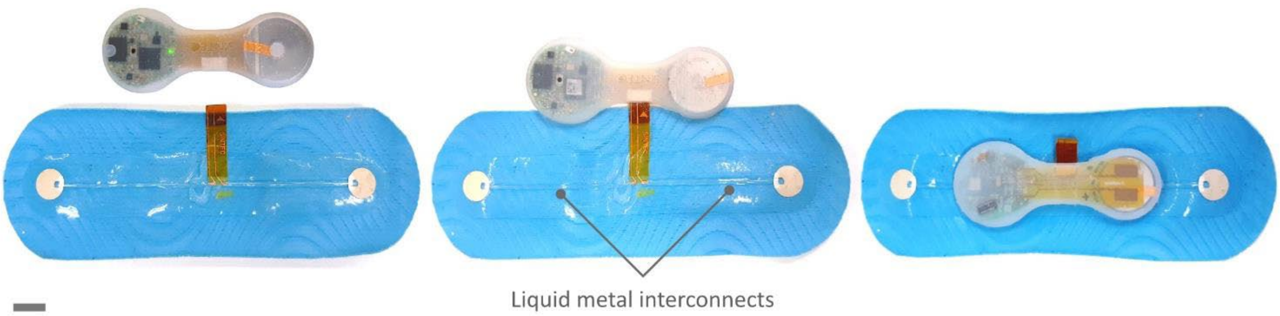

Figure 1 - Photographs of the wireless wearable device consisting of the electronic module and the soft and stretchable sensor patch with patterned liquid metal interconnects for electrophysiological readouts. The scale bar corresponds to 1 cm.

Acknowledgement:

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Fat in body-centric communication: The paradigm shift of Fat-IBC in intrabody microwave communication technology

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For the past decades, serving the needs of real-time monitoring, drug delivery, sensing for pre-emptive measures, and providing a better quality of living to the population, research in Intrabody Communication has been done extensively. The applications are not just limited to health care but also span the areas of recreation, sports and information technology. So far, a handful of intra-body, specifically human body-centric (HBC) communication modalities, have been developed, namely galvanic, capacitive and inductive methods. The human body or part of it is used as a communication channel in these technologies. Though they offer the possibility to connect devices and transfer data wirelessly from one part of the body to the other, they suffer from one common drawback: low bandwidth and lower data rates. Radiofrequency communication has been regarded until recently as an improbable candidate for extensive HBC applications. In 2016 Asan et al. from the Microwaves in Medical Engineering Group, Uppsala University, Sweden, published their first paper on the feasibility of using adipose tissue to transmit Microwave signals inside the body with significantly low loss(2dB/cm) [1]. Since then, a number of articles have been published on different aspects of fat–intrabody communication (Fat-IBC) [2-6]. Considering the human anatomy, the subcutaneous fat tissue is sandwiched between denser tissues such as skin and muscle. As it is known that fat, due to its very low water content, has low permittivity and losses, while muscle and skin do have almost an order of magnitude higher permittivity and losses which are three to four times that of fat. This creates a natural wave-guiding structure that can be utilised to transmit microwave signals at ISM frequencies. Fat- IBC pushes the current limits in intrabody data transfer further by providing higher bandwidth and enabling better power management to ensure longer implanted battery life. Fat channel communication will also substantially help the development of artificial limbs, which require the transfer of high-volume electrophysiological data wirelessly.

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"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Runners Sleep Performance correlation

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Sleep is a crucial factor in athletic performance and recovery. Monitoring sleep patterns can provide valuable information on an athlete's training load and help prevent overtraining and injury. However, current methods for measuring training load require subjective inputs and are often impractical for daily use. This paper proposes to estimate training load by analyzing sleep patterns using commercial off-shelf smartwatches.

The proposed method used sleep scoring from wearable devices (Fitbit smartwatches), and once processed, the participants' sleep performance correlation was estimated. The algorithm was developed and validated using an online dataset from a cohort of amateur athletes over five months.

Results showed that the proposed method could accurately discriminate participants' mean training load based on sleep patterns with an average relative error of 1.53% with respect to the performances evaluated with the reduced Banister method.

The proposed method has several potential applications, including optimizing training programs, preventing injury, and improving overall athletic performance. The method has been tested and evaluated the day-next performances, showing, in some cases, some correlation. Future work will focus on refining the algorithms able to perform the sleep analysis without standalone to integrate them into a commercial smartphone application.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Semi-shielded chamber for fat-intrabody communication (Fat-IBC)

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In this work, a customized portable semi-shielded chamber for torso phantoms to evaluate fat-intrabody communication (Fat-IBC) is presented. Fat-IBC is a technology where human fat tissue is used for microwave communication with intrabody medical devices. Consequently, the separation wall has to be formed according to the shape of the torso phantom, or for the case of the performance measurements, as a solid wall dividing the semi-shielded chamber into two equally large volumes. The performance of the separation wall and the external walls of the semi-shielded chamber was measured using double ridged broadband waveguide horn antennas and monopole antennas.

Fat IBC is a novel technique that can be used to connect devices wirelessly using microwave transmission technique on/off the human body in various tissues. The communication systems consist of a transmitter, receiver and a communication channel. The communication channel is the fat layer between skin and muscle. The fat layer is considered to be a less lossy medium than skin and muscle. It acts as a waveguide for microwave transmission.

A computer simulation of the semi-shielded chamber is made and the efficiency of the chamber is measured [1]. The evaluation of semi-shielded chamber involves three separate aspects for the chamber: shield attenuation, field uniformity, and site voltage standing wave ratio (VSWR).

The proposed semi-shielded chamber can be used in the experimental setup for evaluation of offbody, onbody, and inbody communication. It offers a useful setup for Fat-IBC in the areas of brain-computer interface, brain-machine interface, BANs, medical imaging, and body sensor networks (BSN), and related applications such as central nervous system (brain and spine) communication, cardiovascular disease monitoring, and metabolic disorder control.

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"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Design and developments considerations for vital sign patches

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In this work, a customized portable semi-shielded chamber for torso phantoms to evaluate fat-intrabody communication Yearly 41 million deaths worldwide are caused by non-communicable, often also called invisible, diseases (cardiovascular and respiratory diseases, cancer, diabetes, and mental health conditions) [1]. It is known that the causes often could have been avoided, especially among the people under the age of 70. By continuous monitoring of one's health status, we can assess the real-time health condition and make conscious choices on treatment and preventive self-care.

Wearables with monitoring quality at medical grade, as e.g., plasters with glucose sensing or cardiological monitoring, have catapulted the market with an expected exponential growth on global scale, for health patches. Advancements in sensors, wearables, algorithms and general miniaturization and material understanding of electrical systems [2] has provided the possibility for real-time biosensor read-out within a more practical form factor. Still, today, most health patches monitor one or few bio-signals for a few days of wear. However, by continuously assessing real-time data of multiple bio-signals, we get a deeper insight of the health status. The challenges for increased sensor input are not only the complexity within acquisition, data analysis and power consumption but also creating a robust and flexible body network where besides monitoring quality, the wear comfort, fit, and design are essential factors in determining the user acceptance and therefore success of a product.

In this poster we will discuss the challenges and approaches for designing and developing smart patches for long term wear, reaching towards weeks of continuous wear. We will address the system architecture and design of the flexible and stretchable parts of the patch, the criteria and selection methods for skin-contact materials (Figure 1), while having focus on production methods suitable for scalability to large volume production to serve the increasing global need of continuous health monitoring. We will use our health patch platform Nighthawk (Figure 2), as an example for analysing the development considerations for wearable systems for medical grade continuous monitoring of bio-signals.

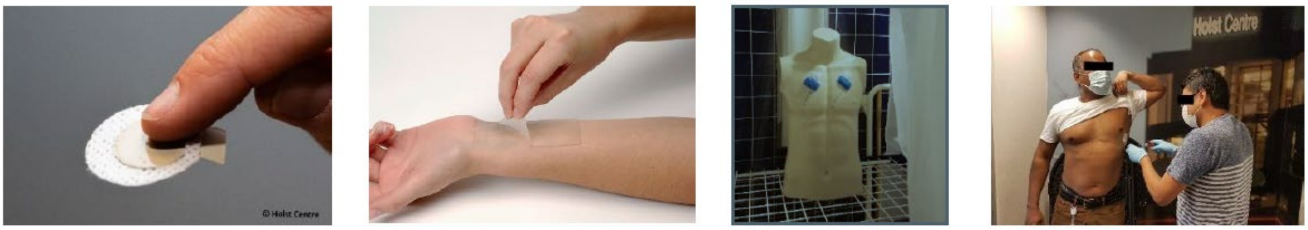

Figure 1. Materials and test procedures for selecting and validating patch design, wear comfort and sensing capabilities.

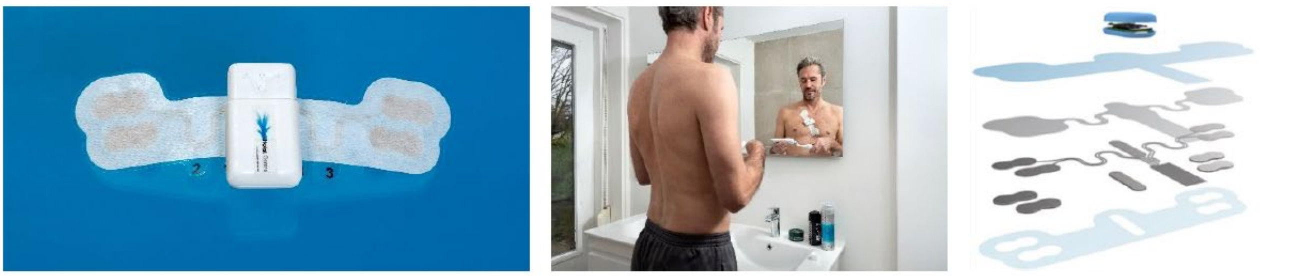

Figure 2. The Nighthawk health patch platform with dry adhesive electrodes for continuous and remote monitoring of ECG and bio-impedance during multiday wear time.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Nanocellulose based piezoelectric device towards wearable applications

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Piezoelectric materials and devices have revealed great significance in different fields such as industrial fabrications, medical appliances, military gadgets, information, and telecommunications because of their property of coupling electrical and mechanical signals. The piezoelectric materials show this property in two ways. The first one is direct piezoelectric effect, where a mechanical stress can be converted into electricity, that is useful for energy harvesters and sensors. The second one is converse piezoelectric effect, where an electric field can be converted to a mechanical strain, that is useful for actuators. The coupling strength between this mechanical and electrical conversions can be defined by piezoelectric coefficient. Piezoelectric polymers are appropriate for different biological applications such as biological signal monitoring, tissue regeneration etc. The most studied piezoelectric polymers are polyvinylidene fluoride (PVDF) and its copolymers as they have good piezoelectric coefficient (~30 pC/N). But PVDF and its copolymers are fluorinated polymers and not biodegradable. They produce toxic fluoride during thermal degradation that is a matter of great concern for the ecosystem. Different biopolymers are being explored as renewable and environmentally friendly piezoelectric polymers. To make low cost, environmentally friendly and bio-compatible piezoelectric sensors that is suitable for large-scale disposable applications, new generation of green piezoelectric polymers are needed.

Among different biopolymers most promising is cellulose, as it is the most abundant, cost-effective, thermally stable biomaterial, has been predicted to have piezoelectric property.[1] In recent years, cellulose and its derivatives have been successfully applied as functional polymers in almost every research fields, including batteries, flexible devices, optics, supercapacitors because it is renewable, biocompatible and cause minimum damage to the environment during processing and disposal. Cellulose is a wonderful alternative for other polymers for a sustainable environment that can help in delaying the environmental damage. However, the piezoelectric coefficient of wood-based materials is low (typically ~0.1 pC/N) as reported first by Bazenhov in 1950,1 which is the main drawback for their practical applications.[2] Recently, guided by the development of nanotechnology, the cellulose industry has developed nanocellulose (cellulose nanocrystal (CNC) and cellulose nanofibers (CNF)) extracted from wood. Those nanocelluloses possess unique advantages compared to the bulk composition, such as chirality, high surface area, lightweight and transparency.[3] Moreover, the presence of nanocrystalline cellulose (CNC) in fibers has been identified as the main reason account for the observed piezoelectric properties in wood-based materials; and isolated CNC could display piezoelectric performance as good as PVDF.[4]

The origin of the large piezoelectric coefficient in cellulose is the dipole moment from hydroxyl group give the cellulose non centrosymmetric crystal structure.5 The alignment of the dipoles in the cellulose chains is very important to improve the piezoelectric property. But the alignment is not easy as it is very difficult to orient because of the compound and sturdy intra and inter molecular hydrogen bonds in between the chains. In this work, electrochemical poling process is demonstrated that is different from conventional poling of ferroelectric materials, that helps to align the nanocrystals inside cellulose nanofibrils by breaking the amorphous part of CNF close to the electrode. As a result of the electrochemical poling great enhancement of the piezoelectric property of CNF thin films has been achieved.6 Macroscopic devices of CNF film were prepared and compared its performance with P(VDF-TrFE) based piezoelectric devices of similar thickness. The CNF device give similar output performance as the P(VDF-TrFE) based piezoelectric devices. The presence of absorbed water from air is important for the breaking of the amorphous part and reorientation of the crystalline part of CNF film as result of the electrochemical reactions under applied poling voltage. Atomic force microscopy (AFM) discloses change of CNF film morphology after the process of electrochemical poling. The mechanism of electrochemical poling is further supported by impedance spectroscopy and grazing- incidence small-angle X-ray scattering (GISAXS) measurements. The piezoelectric coefficient (d33) of CNF thin films is evaluated to be 46 pm V^{-1} using piezoresponse force microscopy (PFM). This d33 value is comparable to that of P(VDF-TrFE) (45 pm V^{-1}). Our work demonstrates the possibility of using cellulose as an alternative material for piezoelectric fluoropolymers. We have made the flexible CNF based piezoelectric device with the same material and method. The device is flexible and can serve as wearable devices for sensor and actuator applications. So, the final nanocellulose based flexible piezoelectric devices will be completely bio-compatible and environmentally friendly.

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"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

Feasibility of conductive embroidered threads for I²C sensors in microcontroller-based wearable electronics

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In recent years, the importance of flexible and textile electronics in the field of wearable devices has continuously increased, as they are expected to replace conventional wires that exhibit limited resistance to the mechanical stress occurring in on-body applications. Wearable Health Devices (WHDs) can provide physiological information about various body parts and employ distributed sensor networks. Among the sensors typically integrated within WHDs, those based on the I²C communication protocol are very common and exploit signals transmitted at frequencies up to hundreds of kilohertz. Therefore, robust communication is required to guarantee a proper transmission of the signal at those frequencies. In this context, we have realized embroidered conductive threads exhibiting a lower resistance, appositely designed to replace conventional wires in a microcontroller-based wearable device employing I²C sensors. A commercial conductive thread (silver coated polyamide) was used to embroider the conductive lines on to cotton fabric. Preliminary measurements were performed to characterize the response of these materials to signals typically operated within the I²C communication protocol at different path lengths. Resistive measurements have also been performed to simulate different environmental conditions, that is, temperature, the effect of sweating, and repeated washing cycles, also apply mechanical stress, i.e., twisting, with promising results that validate our conductive paths for digital signal communication.

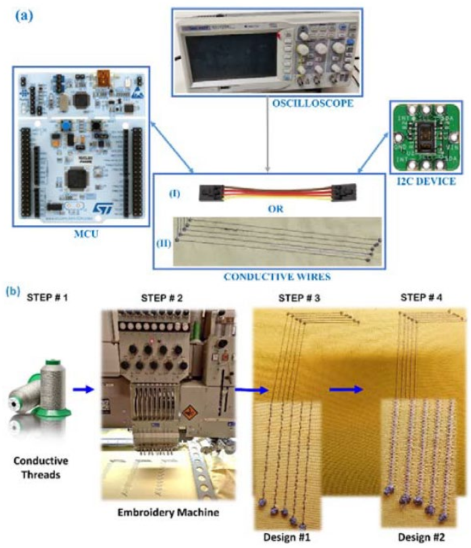

Figure 1: (a) An illustration of the experimental set up: the microcontroller shares SDA and SCL signals to I2C device by two separate I2C ports using commercial copper (I) and embroidered (II) wires, acquiring signals present in both lines with oscilloscope. (b) Schematic representation of step-by-step process of embedding conductive yarns into textile through embroidering technique.

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"This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824984"

Artificial Tactile Nervous System

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The tactile peripheral nervous system innervating human hands, which is essential for sensitive haptic exploration and dexterous object manipulation, features overlapped receptive fields in the skin, arborization of peripheral neurons and many-to-many synaptic connections. Inspired by the structural features of the natural system, we report a supersensitive artificial slowly adapting tactile afferent nervous system based on the triboelectric nanogenerator technology. Using tribotronic transistors in the design of mechanoreceptors, the artificial afferent nervous system exhibits the typical adapting behaviours of the biological counterpart in response to mechanical stimulations. The artificial afferent nervous system is self-powered in the transduction and event-driven in the operation. Moreover, it has inherent proficiency of neuromorphic signal processing, delivering a minimum resolvable dimension two times smaller than the inter-receptor distance which is the lower limit of the dimension that existing electronic skins can resolve. These results open up a route to scalable neuromorphic skins aiming at the level of human's exceptional perception for neurorobotic and neuroprosthetic applications.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824984"

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