Vincent G. Duffy (Ed.)

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Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management

14th International Conference, DHM 2023
Held as Part of the 25th HCI International Conference, HCII 2023
Copenhagen, Denmark, July 23–28, 2023
Proceedings, Part I

Part I

HCI 2023 INTERNATIONAL

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Editor

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Foreword

Human-computer interaction (HCI) is acquiring an ever-increasing scientific and industrial importance, as well as having more impact on people's everyday lives, as an ever-growing number of human activities are progressively moving from the physical to the digital world. This process, which has been ongoing for some time now, was further accelerated during the acute period of the COVID-19 pandemic. The HCI International (HCII) conference series, held annually, aims to respond to the compelling need to advance the exchange of knowledge and research and development efforts on the human aspects of design and use of computing systems.

The 25th International Conference on Human-Computer Interaction, HCI International 2023 (HCII 2023), was held in the emerging post-pandemic era as a 'hybrid' event at the AC Bella Sky Hotel and Bella Center, Copenhagen, Denmark, during July 23–28, 2023. It incorporated the 21 thematic areas and affiliated conferences listed below.

A total of 7472 individuals from academia, research institutes, industry, and government agencies from 85 countries submitted contributions, and 1578 papers and 396 posters were included in the volumes of the proceedings that were published just before the start of the conference, these are listed below. The contributions thoroughly cover the entire field of human-computer interaction, addressing major advances in knowledge and effective use of computers in a variety of application areas. These papers provide academics, researchers, engineers, scientists, practitioners and students with state-of-the-art information on the most recent advances in HCI.

The HCI International (HCII) conference also offers the option of presenting 'Late Breaking Work', and this applies both for papers and posters, with corresponding volumes of proceedings that will be published after the conference. Full papers will be included in the 'HCII 2023 - Late Breaking Work - Papers' volumes of the proceedings to be published in the Springer LNCS series, while 'Poster Extended Abstracts' will be included as short research papers in the 'HCII 2023 - Late Breaking Work - Posters' volumes to be published in the Springer CCIS series.

I would like to thank the Program Board Chairs and the members of the Program Boards of all thematic areas and affiliated conferences for their contribution towards the high scientific quality and overall success of the HCI International 2023 conference. Their manifold support in terms of paper reviewing (single-blind review process, with a minimum of two reviews per submission), session organization and their willingness to act as goodwill ambassadors for the conference is most highly appreciated.

This conference would not have been possible without the continuous and unwavering support and advice of Gavriel Salvendy, founder, General Chair Emeritus, and Scientific Advisor. For his outstanding efforts, I would like to express my sincere appreciation to Abbas Moallem, Communications Chair and Editor of HCI International News.

July 2023 Constantine Stephanidis

HCI International 2023 Thematic Areas and Affiliated Conferences

Thematic Areas

- HCI: Human-Computer Interaction
- HIMI: Human Interface and the Management of Information

Affiliated Conferences

- EPCE: 20th International Conference on Engineering Psychology and Cognitive Ergonomics
- AC: 17th International Conference on Augmented Cognition
- UAHCI: 17th International Conference on Universal Access in Human-Computer Interaction
- CCD: 15th International Conference on Cross-Cultural Design
- SCSM: 15th International Conference on Social Computing and Social Media
- VAMR: 15th International Conference on Virtual, Augmented and Mixed Reality
- DHM: 14th International Conference on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management
- DUXU: 12th International Conference on Design, User Experience and Usability
- C&C: 11th International Conference on Culture and Computing
- DAPI: 11th International Conference on Distributed, Ambient and Pervasive Interactions
- HCIBGO: 10th International Conference on HCI in Business, Government and Organizations
- LCT: 10th International Conference on Learning and Collaboration Technologies
- ITAP: 9th International Conference on Human Aspects of IT for the Aged Population
- AIS: 5th International Conference on Adaptive Instructional Systems
- HCI-CPT: 5th International Conference on HCI for Cybersecurity, Privacy and Trust
- HCI-Games: 5th International Conference on HCI in Games
- MobiTAS: 5th International Conference on HCI in Mobility, Transport and Automotive Systems
- AI-HCI: 4th International Conference on Artificial Intelligence in HCI
- MOBILE: 4th International Conference on Design, Operation and Evaluation of Mobile Communications

List of Conference Proceedings Volumes Appearing Before the Conference

1. LNCS 14011, Human-Computer Interaction: Part I, edited by Masaaki Kurosu and Ayako Hashizume
2. LNCS 14012, Human-Computer Interaction: Part II, edited by Masaaki Kurosu and Ayako Hashizume
3. LNCS 14013, Human-Computer Interaction: Part III, edited by Masaaki Kurosu and Ayako Hashizume
4. LNCS 14014, Human-Computer Interaction: Part IV, edited by Masaaki Kurosu and Ayako Hashizume
5. LNCS 14015, Human Interface and the Management of Information: Part I, edited by Hirohiko Mori and Yumi Asahi
6. LNCS 14016, Human Interface and the Management of Information: Part II, edited by Hirohiko Mori and Yumi Asahi
7. LNAI 14017, Engineering Psychology and Cognitive Ergonomics: Part I, edited by Don Harris and Wen-Chin Li
8. LNAI 14018, Engineering Psychology and Cognitive Ergonomics: Part II, edited by Don Harris and Wen-Chin Li
9. LNAI 14019, Augmented Cognition, edited by Dylan D. Schmorrow and Cali M. Fidopiastis
10. LNCS 14020, Universal Access in Human-Computer Interaction: Part I, edited by Margherita Antona and Constantine Stephanidis
11. LNCS 14021, Universal Access in Human-Computer Interaction: Part II, edited by Margherita Antona and Constantine Stephanidis
12. LNCS 14022, Cross-Cultural Design: Part I, edited by Pei-Luen Patrick Rau
13. LNCS 14023, Cross-Cultural Design: Part II, edited by Pei-Luen Patrick Rau
14. LNCS 14024, Cross-Cultural Design: Part III, edited by Pei-Luen Patrick Rau
15. LNCS 14025, Social Computing and Social Media: Part I, edited by Adela Coman and Simona Vasilache
16. LNCS 14026, Social Computing and Social Media: Part II, edited by Adela Coman and Simona Vasilache
17. LNCS 14027, Virtual, Augmented and Mixed Reality, edited by Jessie Y. C. Chen and Gino Fragomeni
18. LNCS 14028, Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management: Part I, edited by Vincent G. Duffy
19. LNCS 14029, Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management: Part II, edited by Vincent G. Duffy
20. LNCS 14030, Design, User Experience, and Usability: Part I, edited by Aaron Marcus, Elizabeth Rosenzweig and Marcelo Soares
21. LNCS 14031, Design, User Experience, and Usability: Part II, edited by Aaron Marcus, Elizabeth Rosenzweig and Marcelo Soares

22. LNCS 14032, Design, User Experience, and Usability: Part III, edited by Aaron Marcus, Elizabeth Rosenzweig and Marcelo Soares
23. LNCS 14033, Design, User Experience, and Usability: Part IV, edited by Aaron Marcus, Elizabeth Rosenzweig and Marcelo Soares
24. LNCS 14034, Design, User Experience, and Usability: Part V, edited by Aaron Marcus, Elizabeth Rosenzweig and Marcelo Soares
25. LNCS 14035, Culture and Computing, edited by Matthias Rauterberg
26. LNCS 14036, Distributed, Ambient and Pervasive Interactions: Part I, edited by Norbert Streitz and Shin'ichi Konomi
27. LNCS 14037, Distributed, Ambient and Pervasive Interactions: Part II, edited by Norbert Streitz and Shin'ichi Konomi
28. LNCS 14038, HCI in Business, Government and Organizations: Part I, edited by Fiona Fui-Hoon Nah and Keng Siau
29. LNCS 14039, HCI in Business, Government and Organizations: Part II, edited by Fiona Fui-Hoon Nah and Keng Siau
30. LNCS 14040, Learning and Collaboration Technologies: Part I, edited by Panayiotis Zaphiris and Andri Ioannou
31. LNCS 14041, Learning and Collaboration Technologies: Part II, edited by Panayiotis Zaphiris and Andri Ioannou
32. LNCS 14042, Human Aspects of IT for the Aged Population: Part I, edited by Qin Gao and Jia Zhou
33. LNCS 14043, Human Aspects of IT for the Aged Population: Part II, edited by Qin Gao and Jia Zhou
34. LNCS 14044, Adaptive Instructional Systems, edited by Robert A. Sottilare and Jessica Schwarz
35. LNCS 14045, HCI for Cybersecurity, Privacy and Trust, edited by Abbas Moallem
36. LNCS 14046, HCI in Games: Part I, edited by Xiaowen Fang
37. LNCS 14047, HCI in Games: Part II, edited by Xiaowen Fang
38. LNCS 14048, HCI in Mobility, Transport and Automotive Systems: Part I, edited by Heidi Krömker
39. LNCS 14049, HCI in Mobility, Transport and Automotive Systems: Part II, edited by Heidi Krömker
40. LNAI 14050, Artificial Intelligence in HCI: Part I, edited by Helmut Degen and Stavroula Ntoa
41. LNAI 14051, Artificial Intelligence in HCI: Part II, edited by Helmut Degen and Stavroula Ntoa
42. LNCS 14052, Design, Operation and Evaluation of Mobile Communications, edited by Gavriel Salvendy and June Wei
43. CCIS 1832, HCI International 2023 Posters - Part I, edited by Constantine Stephanidis, Margherita Antona, Stavroula Ntoa and Gavriel Salvendy
44. CCIS 1833, HCI International 2023 Posters - Part II, edited by Constantine Stephanidis, Margherita Antona, Stavroula Ntoa and Gavriel Salvendy
45. CCIS 1834, HCI International 2023 Posters - Part III, edited by Constantine Stephanidis, Margherita Antona, Stavroula Ntoa and Gavriel Salvendy
46. CCIS 1835, HCI International 2023 Posters - Part IV, edited by Constantine Stephanidis, Margherita Antona, Stavroula Ntoa and Gavriel Salvendy

47. CCIS 1836, HCI International 2023 Posters - Part V, edited by Constantine Stephanidis, Margherita Antona, Stavroula Ntoa and Gavriel Salvendy

https://2023.hci.international/proceedings

Preface

Software representations of humans, including aspects of anthropometry, biometrics, motion capture and prediction, as well as cognition modeling, are known as Digital Human Models (DHM), and are widely used in a variety of complex application domains where it is important to foresee and simulate human behavior, performance, safety, health and comfort. Automation depicting human emotion, social interaction and functional capabilities can also be modeled to support and assist in predicting human response in real-world settings. Such domains include medical and nursing applications, work, education and learning, ergonomics and design, as well as safety and risk management.

The 14th Digital Human Modeling & Applications in Health, Safety, Ergonomics & Risk Management (DHM) Conference, an affiliated conference of the HCI International Conference 2023, encouraged papers from academics, researchers, industry and professionals, on a broad range of theoretical and applied issues related to Digital Human Modeling and its applications.

The research papers contributed to this year's volumes span across different fields that fall within the scope of the DHM Conference. The study of DHM issues in various application domains has yielded works emphasizing human factors and ergonomics based on human models, novel approaches in healthcare, and the application of Artificial Intelligence in medicine. Applications of interest are shown across many industries. Job design and productivity, robotics and intelligent systems are among the human-technology modeling and results reporting efforts this year.

Two volumes of the HCII 2023 proceedings are dedicated to this year's edition of the DHM Conference. The first volume focuses on topics related to human factors and ergonomics, job design and human productivity, as well as interaction with robots and exoskeletons. The second volume focuses on topics related to digital health, IoT and AI in medicine and healthcare, as well as modeling complex human behavior and phenomena.

Papers of these volumes are included for publication after a minimum of two single–blind reviews from the members of the DHM Program Board or, in some cases, from members of the Program Boards of other affiliated conferences. I would like to thank all of them for their invaluable contribution, support and efforts.

July 2023 Vincent G. Duffy

14th International Conference on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management (DHM 2023)

The full list with the Program Board Chairs and the members of the Program Boards of all thematic areas and affiliated conferences of HCII2023 is available online at:

http://www.hci.international/board-members-2023.php

HCI International 2024 Conference

The 26th International Conference on Human-Computer Interaction, HCI International 2024, will be held jointly with the affiliated conferences at the Washington Hilton Hotel, Washington, DC, USA, June 29 – July 4, 2024. It will cover a broad spectrum of themes related to Human-Computer Interaction, including theoretical issues, methods, tools, processes, and case studies in HCI design, as well as novel interaction techniques, interfaces, and applications. The proceedings will be published by Springer. More information will be made available on the conference website: http://2024.hci.international/.

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https://2024.hci.international/

Contents – Part I

Contents – Part II

Modeling Complex Human Behavior and Phenomena

Human Factors and Ergonomics

TWINMED T-SHIRT, a Smart Wearable System for ECG and EMG Monitoring for Rehabilitation with Exoskeletons

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Abstract. Wearable devices have become increasingly popular in recent years and have been utilized in a range of different fields, including healthcare, fitness, and entertainment. In particular, the development of smart textiles has been a major breakthrough in the wearable technology industry. This paper discusses the design and development of a wearable system for muscular and cardio-respiratory evaluation for rehabilitation with exoskeleton.

The paper is focus on the Twinmed system which consists in an exoskeleton and a smart t-shirt that records cardiac and muscle signals through silver-based 3D textile electrodes. The t-shirt has been designed tailored onto the patient's measurements for optimal sensor placement, and each sensor is connected to a device that can monitor the two main signals: muscular and cardiac.

The system was developed with a focus on evaluating the progress of rehabilitation and proper use of crutches during exoskeleton walking. All the design features have been selected through collaboration and interaction with project stockholders: patients, therapists, and engineers. The system has been pretested in laboratory both without and with the exoskeleton and have been shown to be effective for monitoring EMG signals and provide physicians with a clearer view of the cardiovascular exertion required, while allowing patients to have quantitative feedback on their health status.

Keywords: Rehabilitation · Wearable device · Exoskeleton

1 The Twinmed System

1.1 The System

Wearable devices for rehabilitation are quickly becoming an integral part of modern health care. These devices can provide users with accurate data and feedback on their physical condition and progress, allowing medical professionals to better track and monitor their patient's progress. Wearable devices can be used to track movement, posture, and range of motion, as well as other important health metrics [1]2.

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Physical rehabilitation can include helping with physical therapy, as well as helping patients recover from injuries or surgery. Additionally, wearable devices can help to provide patients with more motivation to take part in their rehabilitation, as they can see their progress and results in real time [3, 4].

Wearable devices are also becoming more personalized, with some devices being specifically designed for certain conditions [5]. For example, devices designed for physical rehabilitation can measure more specific metrics related to a patient's specific condition, allowing medical professionals to track progress more accurately.

In this paper authors report the design and test process for a new wearable system based on a smart t-shirt. The system has been designed specifically for supporting and evaluating the patient during the rehabilitation process with an exoskeleton.

This research is part of a project funded by INAIL (National institute for insurance against industrial injuries) which starts from a previous project who seen the development of a new modular exoskeleton by Rehab Technologies Lab IIT-INAIL (Genova, Italy). The project TWIN [6] consist in a novel modular lower limb exoskeleton for personal use of spinal-cord injury (SCI) subjects. The exoskeleton was designed based on features requested by users during participatory investigation which were attended by patients, engineers, designers and therapists. The TWIN exoskeleton was therefore designed to have the following characteristics (lightweight and portability, quick and autonomous wearing and setup, cost effectiveness, long battery life, comfort and safety, and especially stability during standing and walking). Figure 1 shows the TWIN exoskeleton in action.

Fig. 1: The exoskeleton Twin without the smart t-shirt

In the last years, the use of robots and exoskeletons for rehabilitation is becoming more common, but very often only the orthopedic and neurological aspects are considered, leaving out the whole cardiovascular aspect instead.

In this kind of rehabilitation, it is important to consider the potential risks to the cardiovascular system. When individuals use exoskeletons, they are often engaging in physical activity that they might not be able to perform unassisted; this can lead to an increase in heart rate, blood pressure, and cardiac output, which can put additional stress on the cardiovascular system, which in most cases comes from periods of inactivity due to post-surgery or post-disease course. Mulroy et al. [7] that patients with spinal cord injuries who used exoskeletons for walking experienced an increase in heart rate and blood pressure. The study also found that the patients had a higher cardiac output during exoskeleton-assisted walking compared to walking without the exoskeleton. These findings suggest that the use of exoskeletons for rehabilitation can put additional stress on the cardiovascular system; the authors concluded that the use of robots for rehabilitation should be carefully monitored to avoid any adverse effects on the cardiovascular system.

It is important to note that while the use of robots and exoskeletons for rehabilitation can be beneficial for patients, it can also pose risks to their cardiovascular health. Patients with pre-existing cardiovascular conditions, such as hypertension or heart disease, may be at higher risk for adverse effects. Therefore, it is important to carefully evaluate patients before using these devices and to monitor their cardiovascular health throughout the rehabilitation process. Medical professionals should also be aware of the potential risks and take appropriate precautions to ensure patient safety.

It has also been pointed out that in many cases, during the use of rehabilitation robots or exoskeletons on patients with spinal injuries there is an increase in extrasystoles that go to further highlight the danger of using these systems if not properly supervised.

2 Design the T-shirt

As described in the previous section, cardio-respiratory monitoring during rehabilitation exercise with robots and exoskeletons is of paramount importance to prevent risky events for patients. On the other hand, another critically important aspect in rehabilitation is clinical adherence to therapy, that is, in case of rehabilitation, how committed the patient is to continue with the exercises assigned to him or her by the therapist over time. The issue that most often plagues those who do home rehabilitation, or tele-rehabilitation, is dropout: on the one hand because progress is not always immediately visible, and on the other hand because the exercises that are usually offered are repetitive and boring.

The wearable system described in this paper has the main goal of heuristic patient monitoring. To optimize the type of measurements and the number of signals acquired, the system was designed by considering the users from the first stages.

By user we mean not only the end users, i.e., patients, but all stakeholders who are part of the group of people who design, configure, install, and use the system.

To do this, the so-called double diamond methodology, or rather, in this case, triple diamond [8] was tapped, which is especially applicable to hardware and software design context.

The Triple Diamond methodology is a design thinking approach that builds on the Double Diamond methodology. The key difference between the Triple and Double Diamond models is that the Triple Diamond places a greater emphasis on implementation and delivery, whereas the Double Diamond focuses more heavily on ideation and problem-solving. The Double Diamond model consists of two main stages: discover and define, with a focus on exploring the problem and generating ideas. The Triple Diamond model adds a third stage, deliver, which emphasizes the importance of implementing and delivering a solution that meets the needs of the users and the business.

The Triple Diamond model consists of three main stages: discovery, define, and deliver. Each of these stages is further broken down into specific steps [9].

The first stage, discovery, is about understanding the problem and the context in which it exists. This stage involves research, observation, and empathy to gain insights into the problem and the people affected by it. The goal is to identify the real problem to be solved and the opportunities for innovation. As described above, in this stage patients and therapist who use exoskeleton were observed in order to extract information and main problems during all the phase of the rehabilitation: preparation, execution and conclusion.

The second stage, define, is about synthesizing the information gathered in the discovery stage to define the problem statement and create a clear design brief. This stage involves analyzing the data collected in the discovery stage and identifying patterns and themes. The goal is to create a clear and actionable problem statement that will guide the ideation and prototyping phases. In order to better understand user's needs, in this second stage we involved all the stakeholder directly in the process by means of focus groups. The focus group was held at a clinical rehabilitation institute and involved physical therapists, physicians, engineers, and patients, for a total of 8 people. During the focus group, physicians stressed the importance of having available, in addition to the electrocardiographic signal, a respiratory signal that can immediately highlight possible fatigue problems.

They also emphasized the need to acquire muscle signals (through surface electromyography) for the upper body only, to highlight how well the patient is walking correctly with the exoskeleton or not, a kind of biofeedback. This last part was the most discussed during the focus group because it needed a trade-off between engineers and clinicians; while from the clinician point of view a lot of EMG signals is necessary to have an optimal analysis of all body movement, there is also a trade-off with the need to make the system portable, small, and wearable. Moreover, another technical problem is related to the type of data transmission to integrate; in fact, if the most widely used technology in wearables is Bluetooth LE, this allows up to a maximum of 7 devices connected simultaneously, thus limiting the number of wearable devices that can be used, and consequently the signals acquired.

The third stage, deliver, is about creating and implementing a solution based on the problem statement and design brief. This stage involves ideation, prototyping, testing, and iteration to create a viable solution. The goal is to create a solution that meets the needs of the users and the business requirements. This last stage, combined with the outcomes from the focus group, emphasized the importance of having the wearable system developed on two fronts: a design related to comfort while using the exoskeleton, and a design related to monitoring.

2.1 Comfort Design

Figure 2 shows the first analysis outcome on the patient using the lower limb exoskeleton. The figure shows a first approach to the design of the wearable system where the positioning for EMG signal acquisition, positioning for ECG and breathing signal acquisition, pressure sensors for measuring discomfort at the thoracic level, and soft parts to decrease discomfort in some areas where the exoskeleton might be uncomfortable are visible.

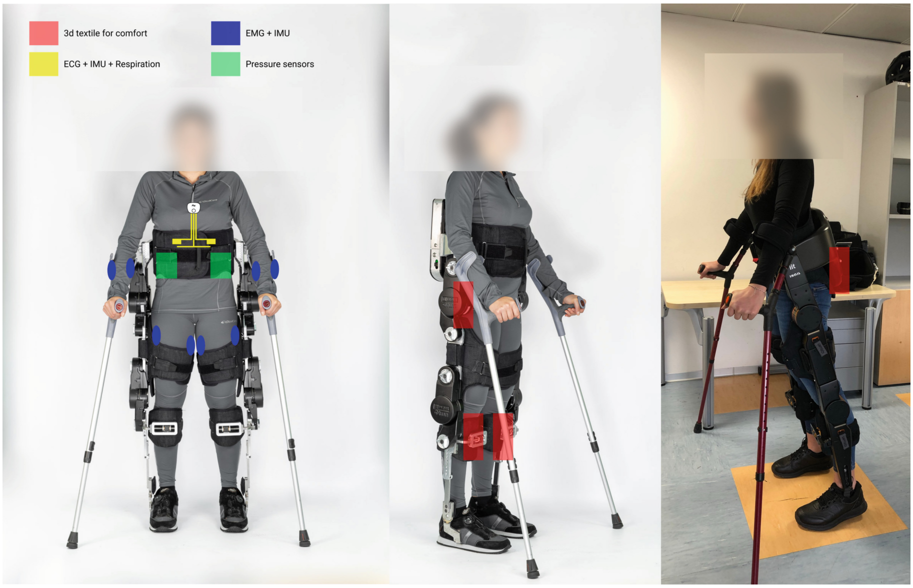

Fig. 2. First design for the wearable design. On the left the signal parts, on the right the comfort part

As visible in the figure, the red rectangle indicates the possible positions underline during the ghosting phase in which the contact of the exoskeleton can be in contact with the patient's body and create discomfort or injuries. After a more thorough analysis with who designed the exoskeleton, thanks in part to modifications built into the braces that hold exoskeleton in place, the points where contact discomfort is possible have decreased. However, the parts below the knee and on the back remaining of possible interference.

Different solutions can be used to minimize discomfort due to the contact between exoskeleton and skin. The pressure generated by this contact may change depending on the size of the patient who wear the exoskeleton. However, having the goal of designing a sensorised t-shirt/suit, the most suitable choice turns out to be the implementation of "special" fabric in the garment that can absorb pressure and work as a protection.

A 3D textile is a fabric that has a three-dimensional structure, usually created by using fibers or yarns of different lengths or by using a variety of weaving or knitting techniques. In garment design, 3D textiles can be used to provide additional protection or cushioning in areas that are prone to impact or wear. They can also be used to provide structural support or to create unique aesthetic effects.

Figure 3 shows and example of 3d textile; the thickness of the fabric is generated by a weave made from fabric with a high polyamide component. Although the fabric is composed mainly of plastic material, a surface finish can be given to make it comfortable. In addition, the texturing of the fabric allows air circulation, so as to avoid heavy sweating that occurs when the worn fabric is synthetic.

Fig. 3. Example of 3d textile applied as comfortable cushion for exoskeleton joint

2.2 Smart T-shirt Design

The second design phase for the smart garment consist in the development of a solution for data acquisition. During the focus group mentioned earlier, a qualitative analysis was carried out regarding what characteristics the garment should have and what signals to acquire. Starting from a design brief shown to the participants in which many more signals than were needed were included (see Fig. 2), the focus group participants opened a discussion by comparing technical and medical needs in order to define a solution that was feasible and at the same time able to monitor the patient optimally. No longer a technology driven design, but a user's-driven design, in which users lead development, focusing resources on what is really needed for the project.

This open discussion among all stakeholders in the project also led to drastic decisions such as removing the sensors from the lower limb, as they were deemed unnecessary for performance monitoring since they are linked to residual or passive activity generated by limb movements via the exoskeleton.

During the focus group, all participants were able to actively be part of the discussion on all the features of the system, including the more technical ones, thanks to the presence of engineers, and designers trained on technology. This made it possible to draft from the first iteration the characteristics that the system should have, including the technological point of view and its feasibility.

The main features are listed below, while Fig. 4 shows the final structure of the wearable system:

1. ECG channel on the 10^{th} rib;
2. Thoracic breath sensor (if possible, also diaphragmatic);
3. Six channel EMG:
   a. Right and left triceps
   b. Right and left deltoid
   c. Right and left middle (or upper) trapezius
4. ECG sample frequency 1 kHz;
5. EMG sample frequency 1 kHz;
6. At least 4 h battery life;
7. Bluetooth connection;
8. Small size;
9. Light weight;
10. Ease of connection with the garment;
11. LED for status.

The wearable system shown in Fig. 4 consists of three devices each capable of measuring two EMG signals, and a fourth device for measuring the ECG signal and respiration. The ECG device also records, through an inertial motion unit, the patient's trunk position. The devices are connected to the T-shirt by means of four snaps buttons each. The snap buttons were preferred over a connection with spring and magnetic probes in order to be able to optimize the measurement of signals, especially EMG signals which are much more sensitive to noise than ECG ones.

Each device has a button for control and an LED that identifies status through color change and flashing. The devices can be connected to a hub through the Bluetooth connection. However, since the signals are acquired with a fairly high sampling rate, the Bluetooth connection is over-used and requires high performance hub with specific characteristics that can support this kind of transmission (e.g.. Bluetooth 5.2 with at least 247 byte MTU, 2M Physical Layer and $<$ 15 ms priority).

The sensorized T-shirt is made of highly elastic fabric, in order to maintain a strong adhesion to the skin and optimize the acquired signals, minimizing disturbances due to movement and rubbing of the electrodes with the skin. The electrodes are made of 3D conductive fabric based on silver. It was chosen to use a 3D conductive fabric instead of a more common plain conductive fabric for two main reasons:

- being three-dimensional and having the component that generates the three-dimensionality also conductive, the characteristics of an electrode made with this fabric approach those of a classic Ag-AgCl electrode (the impedance is much lower than the plain fabric).

- the three-dimensionality creates a sponge effect, which retains water/sweat or electrode gel; this further improves the conductivity of the electrodes and therefore the quality of the signal.

The size of the electrodes is optimized based on the measurement to be taken. The two ECG electrodes (the right leg drive is removed) have a size of 20 × 30 mm. The electrode then narrows to a strip of thickness 10 mm, which is used to transmit the ECG signal from the actual electrode to the automatic button used for connection with the electronic device. The breath sensor is instead composed by a special fiber of TPU charged with graphene ponder. The graphene add conductivity to the fiber that, when subject to stretching or squashing, change. This change in conductivity can be used to monitor fiber elongation; if this fiber is applied to a shirt in the thoracic or diaphragmatic region, the enlargement of the rib cage or diaphragmatic breathing cause a lengthening of the fiber thus making it possible to monitor respiration.

Unlike the ECG signal, the position, shape, and dimension of EMG electrodes are important factors which can affect the signal quality and accuracy of the measurement [10].

The position of EMG electrodes is crucial for obtaining accurate and meaningful data. The electrodes must be placed over the muscle of interest, as close as possible to the motor endplate zone, where the muscle fibers are innervated by the motor neuron. Placement of the electrodes in the optimal position ensures that the recorded signal is representative of the activity of the muscle fibers. The muscle length and orientation of the fibers can also affect the recorded signal. Therefore, it is important to standardize the placement of the electrodes for each muscle group.

The electrode should be large enough to capture the electrical activity of the muscle, but not so large that it picks up signals from neighboring muscles. An electrode that is too small may not pick up enough signal, while an electrode that is too large may pick up signals from other muscles or from the skin. The shape of the electrode can also affect the signal quality, with rounded electrodes being preferred over square or rectangular ones.

Another choice to make when dealing with EMG is whether to use a unipolar or bipolar system. Bipolar EMG consist of three electrodes: two are placed on the skin over the muscle of interest. The third electrode is placed at fixed distance apart from the other two and used as reference.

Unipolar EMG electrodes consist of only two electrodes, one for the measurement and one for the reference. The recording electrodes is placed over the muscle of interest, while the reference electrode is placed on a nearby bone or tendon. This kind of configuration allows for using less electrodes, which is essential when designing a smart garment because it allows to minimize the number of electrodes and, in the case of this specific project, the number of connections between device and garments. Moreover, this type of EMG recording provides more spatial resolution than bipolar ones.

The electrodes on the t-shirt follow the unipolar configuration; the shape, size and position are based on Seniam [11] guidelines.

Fig. 4. The sensorised t-shirt. The devices are connected on the back for trapezius EMG, on the arm for deltoids and triceps, and on the front for ECG and respiration measurement.

3 System Test

To verify the correct functioning of the system, three different types of tests were implemented.

The first test was carried out to verify the feasibility of measuring EMG through textile electrodes in a unipolar configuration, structured according to the Seniam guidelines [11]. To simplify the test operations, instead of monitoring the muscles listed above, it was preferred to measure the EMG on the brachioradialis and ulnar flexor muscles. To do this, a sleeve was made inside which the textile electrodes were positioned, connected to a medical snap button with the possibility of connecting a commercial EMG device. The test protocol involved two consecutive measurements, the first with the sensorised sleeve, and the second with the classic Ag-AgCl electrodes positioned like those present in the sleeve. The subject was asked to isometrically flex and extend the wrist in order to collect the activation of the two muscles. The two signals were subsequently compared to check if the textile electrodes were able to record muscle activation, and fatigue.

The second test was carried out with the aim to verify the correct position of the electrode on the t-shirt. Figure 5 show this test and the EMG signal acquired during gait with crutches. The protocol foresaw the subject wore the sensorized shirt connected to a commercial EMG (FREEMG Wireless surface EMG by BTS Bioengineering) while walking with crutches. The healthy subject simulated a correct walk with crutches and a walk instead with incorrect support of the crutches. The two types of walking activate the muscles in different ways, giving the possibility to have feedback on the correct use of the exoskeleton.

The third test was performed with the exoskeleton. The objective of this latest test was to verify the interferences between the exoskeleton and the smart T-shirt, in order to possibly optimize the position of the electrodes on the shirt. The protocol envisaged the use of EMG devices developed ad-hoc for the project. The test was carried out in two different phases: a first phase with isometric contractions to verify the correct functioning of the system; a second phase in which all signals were acquired during the use of the exoskeletal. All the data have been than processed by means of specific algorithm in order to verify the quality of the signals.

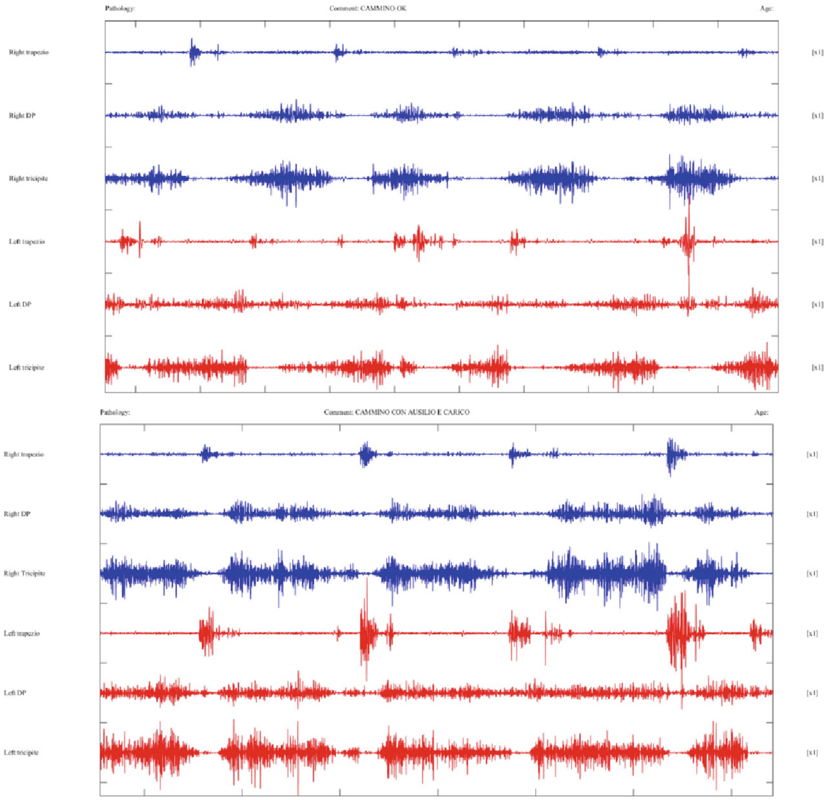

Fig. 5. EMG acquired with the sensorised T-shirt. The first chart shows the activation of the six muscles during the correct use of crouches; the second chart show the activation of the same muscle with wrong support of the crutches.

4 Conclusion

The data recorded during the first two test sessions made it possible to optimize the size and especially the production process of sensors in order to obtain clean signals comparable with the ones recorded through classic modes. The third test has allowed to check if the sensorized T-shirt developed was able to detect the signals during the use of the exoskeleton. The acquired data show an excellent signal quality when the subject uses the exoskeleton but in a static position. During the gait, on the other hand, the exoskeleton interferes with the correct functioning of the sensorised T-shirt. In particular, the signal that is more affected by noise is the cardio-respiratory one. The exoskeleton is in fact anchored to the body by means of a thoracic brace that has the edges exactly near the textile electrodes and the strain gauge. This involves many disorders on the two signals that prevent the correct measure of cardio-respiratory parameters. The modification of the brace or the repositioning of the electrodes in such a way that they are completely covered by the brace, significantly improves the quality of the signal (Fig. 6).

As for EMG signals, the quality is adequate to be able to carry out an analysis on muscles activations. Also in this case, during movements (raised and seat) the handling with crutches causes movements of the T-shirt, with the consequent insertion of signal noise. Moreover, these movements in some cases cause the complete detachment of the electrode (in particular the trapezius), completely preventing the signal measure.

In conclusion, the tests have shown how a sensorised shirt, designed for a specific goal, can be used for monitoring during rehabilitation with exoskeleton. It is mandatory to take into consideration that it is a smart garment, built with conductive textile and that does not use conductive gels to optimize the interface with the skin. It therefore follows that the use of the classic measures obviously has a better signal quality, but at the expense of the usability and quality of life of the wearer, as well as the quality of rehabilitation therapy.

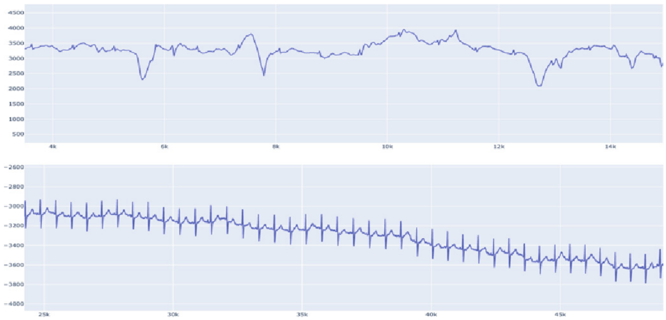

Fig. 6. ECG signals during gait with exoskeleton. The first one is visibly affected by noise generated by the rubbing of thoracic brace on the textile electrodes. The second one shows a clear ECG when electrodes are completely covered by the brace.

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