

# Exoerience

Benchmarking Exoskeleton-Assisted Gait Based on Users' Subjective Perspective and Experience



## EXPERIENCE protocols and PIs documentation

**Document version:** 2.0

**Date:** March 31, 2021

**Authors:** I. Pisotta, N. L. Tagliamonte, A. Bigioni, F. Bentivoglio, I. Pecoraro

**Document type:** Confidential

## Table of contents

<b>EXECUTIVE SUMMARY</b>	<b>4</b>
<b>1 INTRODUCTION</b>	<b>4</b>
1.1 EXPERIENCE objectives	4
<b>2 SCENARIO AND PROTOCOL</b>	<b>5</b>
2.1 Generalities	5
2.2 Sensors	5
2.3 Protocol steps	6
2.3.1 Notes	7
2.4 Controlled variables	7
2.5 EXPERIENCE software overview	7
<b>3 QUESTIONNAIRE DATA SOFTWARE</b>	<b>8</b>
3.1 EXPERIENCE questionnaire	8
3.1.1 Structure and administration	8
3.1.2 Items encoding	9
3.2 Questionnaire data collection software	10
3.2.1 Software installation and run	10
3.2.2 Software use	10
3.3 Questionnaire performance indicators	18
3.3.1 PIs definition	18
3.3.2 PIs calculation	18
3.3.3 PIs input data files	19
3.3.4 Questionnaire PIs visualization software	20
<b>4 PSYCHOPHYSIOLOGICAL DATA SOFTWARE</b>	<b>22</b>
4.1 Physiological data collection software	22
4.1.1 Software installation and run	22

---

4.1.2 Software use	22
<b>4.2 Pre-processing software</b>	<b>24</b>
<b>4.3 Psychophysiological performance indicators</b>	<b>24</b>
4.3.1 PIs definition	24
4.3.2 PIs calculation	25
4.3.3 PIs input data files	25
4.3.4 Psychophysiological PIs visualization software	25
<b>5 DATASET</b>	<b>28</b>
5.1 Subjects overview	28
5.2 Collected data naming	28
5.2.1 Notes	28
5.3 Testing dataset	29
<b>6 APPENDIX A – DATASHEET OF ZEPHYR BIOMODULE 3 SENSOR</b>	<b>30</b>
<b>7 APPENDIX B – DATASHEET OF SHIMMER GSR SENSOR</b>	<b>45</b>
<b>8 APPENDIX C – QUESTIONNAIRE DEFINITIONS</b>	<b>47</b>
8.1 Factor 1: USABILITY	47
8.2 Factor 2: ACCEPTABILITY	47
8.3 Factor 3: PERCEPTIBILITY	48
8.4 Factor 4: FUNCTIONALITY	48

## Executive summary

The present document describes the main outcomes of the EXPERIENCE sub-project, as stated in Task T3.6 ("Activities reporting") of the Description of Work in the Grant Agreement. Information reported in this document complies with the requests stated in Part C – Section 3 of the sub-project Final Report.

Section 1 reports general information on the sub-project and its aims.

Section 2 provides additional details with respect to the excel sheet including information on the protocol, Performance Indicators (PIs) and benchmarking algorithms.

Section 3 describes the software developed to administer a novel multifactor questionnaire to assess the experience of subjects walking with lower limb exoskeletons.

Section 4 describes the software to collect data from physiological sensors and to assess psychophysiological metrics in subjects walking with lower limb exoskeletons.

Section 5 describes the dataset collected during real experiments carried out within the sub-project.

Sections 6-7 include the datasheet of the employed physiological sensors.

Section 8 includes the definitions of the Factors and Sub-Factors of the newly developed multifactor questionnaire.

This first draft version of the document will be improved and updated during the next *Integration* Phase of the sub-project.

## I Introduction

Lower limb exoskeletons are becoming increasingly relevant in rehabilitation and assistive scenarios to augment, train, supplement, or even replace motor functions. These devices have the potentiality to improve the quality of life of people with disabilities.

Recently, experts in the field of robotic rehabilitation consider strongly relevant the analysis of User Subjective Perspective (USP), both from the clinical and engineering point of view. Indeed, it has been acknowledged that the wider acceptance of technologies and satisfaction about them strictly depend on the end-user being central during each step of the design and development process and that the improvement of functionality and usability of devices has to rely on users' personal needs, and more specifically, on their feedback.

Nonetheless, there is a lack of systematic instruments to assess USP during locomotion with exoskeletons and questionnaires used in the literature are adapted from different applications (investigations in the field of Information Technology, IT) and can be hardly used in the framework of exoskeleton-aided walking. Furthermore, tools such as questionnaires and interviews created ad hoc are not validated and are difficult to translate in other scenarios (different exoskeletons or different users). Current research highlights the strong need for a new structured and validated method to assess USP during exoskeletons use and also the importance of measuring physiological data to estimate user's psychophysiological state.

### 1.1 EXPERIENCE objectives

The EXPERIENCE sub-project aims at providing developers of lower-limb exoskeletons and clinical experimenters with a benchmarking method capable of catching the USP of end-users by using a newly developed multifactor questionnaire (EXPERIENCE Questionnaire, EQ) and algorithms to extract psychophysiological indicators based on physiological data. The main outcomes of the sub-project include:

1. A benchmarking software for the user-centered assessment of exoskeleton-assisted overground and treadmill-based walking, divided into two modules:

- Module 1: based on the newly developed multifactor questionnaire;
  - Module 2: algorithms to extract psychophysiological indicators starting from Galvanic Skin Response, the Heart Rate, the Heart Rate Variability and the Respiration Rate.
2. A database collected with healthy subjects and patients\_(stroke/SCI) interacting with:
- Lokomat Pro (Hocoma);
  - Ekso GT (Ekso Bionics).

Details will be provided within this document.

## 2 Scenario and protocol

As requested in Part C – Section 3 of the sub-project Final Report, this section provides details related to the Experience\_Protocol\_PIalgo\_v1.xlsx excel file.

### 2.1 Generalities

The sub-project deals with two different applications. In particular, it develops benchmarking methods for Overground Rehabilitation Exoskeletons (ORE) and Treadmill Rehabilitation Exoskeletons (TRE).

For this reason, the protocol sheet of the excel file has been split in two parts. The aim is the comprehensive and systematic assessment of user subjective experience during exoskeleton-assisted walking by administering the novel multi-factor EQ to derive psychological indicators and by measuring physiological information to compute psychophysiological indicators.

### 2.2 Sensors

Physiological signals are recorded with two commercial devices:

- **ZephyrBioModule 3 sensor:** The datasheet of the sensor is in Appendix A. The [User guide](#) can be downloaded from the manufacturer website.

The device must be connected to a ZephyrTM band that incorporates ECG and breathing sensor (Figure 1).

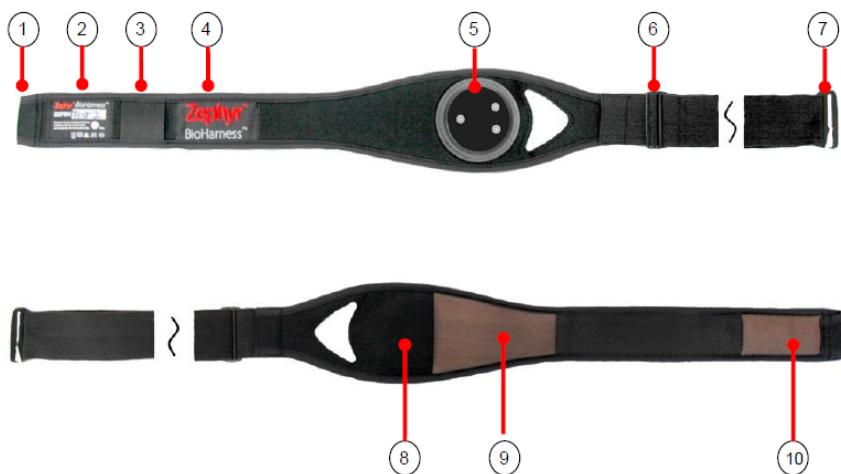


Figure 1: ZephyrBioModule 3 sensor with the ZephyrTM band.

The positioning of the band must be strictly observed and involves aligning the conductive ECG sensor (number 10 in Figure 1) with the center of the chest and the breathing sensor (number 9 in Figure 1) with the left side of

the thorax. For optimal performance, the pad surfaces should be slightly moistened with water to promote conductivity.

- **Shimmer GSR sensor:** the datasheet of the sensor is in Appendix B. The [User guide](#) can be downloaded from the manufacturer website.

The sensor must be attached to the patient's wrist using the adjustable strap. The electrodes must be placed on the back of the index and middle finger of the non-dominant hand (Figure 2).



Figure 2: Shimmer GSR sensor.

## 2.3 Protocol steps

The EXPERIENCE experimental protocol for each *assessment session* is based on the step reported below. The experimenter has to:

1. Place the two physiological sensors onto the subject body (mounting information is reported in Sec. 2.2).
2. Start data collection software and start recording of physiological data (see Sec. 4.1).
3. Put the subject seated with eyes closed and let it relax.
4. Flag the start of the recording of the seated baseline on the data collection software and flag the stop when finished (see Sec. 4.1). Time duration of recording is 4 min and has to be measured by a chronometer (see Sec. 2.4).
5. Place the exoskeleton onto the subject body and let it relax.
6. Flag the start of the recording of the standing baseline on the data collection software and flag the stop when finished<sup>1</sup> (see Sec. 4.1).
7. Start the robot-assisted walking session and wait until steady-state condition is reached. Steady-state condition is reached when assistance parameters are not changed anymore, and the subject is walking comfortably without any major change.
8. Flag the start of the recording of the walking condition on the data collection software and flag the stop when finished (see Sec. 4.1). Time duration of recording is 16 min and has to be measured by a chronometer (see Sec. 2.4).
9. Stop the walking session and stop data collection software (see Sec. 4.1).
10. Remove physiological sensors and exoskeleton.

---

<sup>1</sup> Data recorded in the standing phase has not been used in the calculation of PIs in the current version of the software.

11. Administer the EXPERIENCE questionnaire (see Sec. 3.2).

### 2.3.1 Notes

- The abovementioned protocol for the *assessment sessions* has to be administered after the subject has already undergone at least two *familiarization sessions* to become familiar with the device under testing.
- During *familiarization sessions* a physiotherapist regulates the parameters related to the robotic support according to the participant's needs and residual motor functions.
- Before starting each *assessment session*, subjects have to receive instructions on the questionnaire (definitions of Factors and Sub-Factors) in order to know in advance aspects needing specific focus during the exoskeleton experience and to be prepared for the forthcoming questionnaire administration.
- Each *assessment session* has to be supervised by the same physiotherapist and with the same walking conditions as in the *familiarization session*.
- Two *assessment sessions* (run 1 and run 2) have to be performed, with a maximum time distance of 48 h from each other.
- It is useful to highlight the need to use a uniformed language during the training with the user, in order to simplify the communication and the administration of the questionnaire.

## 2.4 Controlled variables

During the experimental protocol some variables have to be set. This information is encoded in the protocol steps (see Sec. 2.3). Nonetheless, this data can be considered as controlled variables, even if they are not included in the current version of the software.

These variables include:

- Time of recording of physiological data with the subject seated and eyes closed (4 min).
- Time of recording of physiological data with the subject standing and wearing the exoskeleton (4 min).
- Time of recording of physiological data with the subject walking wearing the exoskeleton (16 min).

## 2.5 EXPERIENCE software overview

The software includes two modules: i) Module 1 for the management of questionnaire data and resulting psychological PIs; ii) Module 2 for the management of physiological data and for the calculation of psychophysiological PIs. The structure of the whole benchmarking software is reported in Figure 3.

An additional module (Visualization Tool) has been developed to provide the possibility to directly visualize the computed PIs.

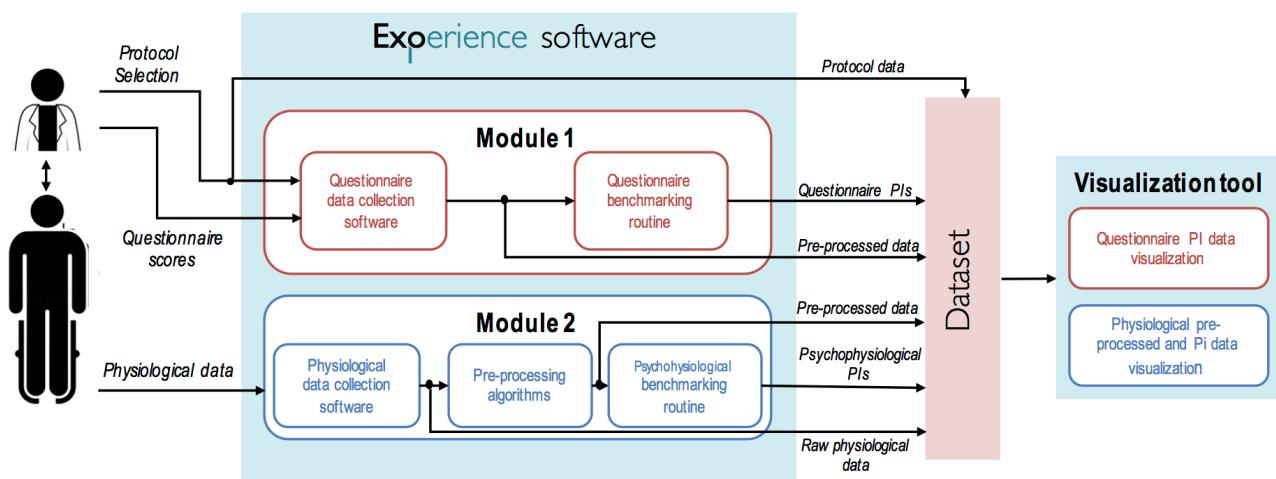


Figure 3: Overview of the structure of the EXPERIENCE software.

The software delivered by the EXPERIENCE sub-project in attachment to the Final Report is:

- **Module 1:** Questionnaire Data Software (Sec. 3)
  - Questionnaire data collection software (collects questionnaire data): `Questionnaire_software.exe`
  - Questionnaire benchmarking routine (calculates questionnaire PIs): `PI_questionnaire.m`
- **Module 2:** Psychophysiological Data Software (Sec. 4)
  - Physiological data collection software (collect physiological data): `Physiological_software.exe`
  - Pre-processing algorithms (pre-process physiological data): `Preprocessing_algorithm.m`
  - Psychophysiological benchmarking routine (calculate psychophysiological PIs): `PI_psychophysiological.m`
- **Visualization tool** (Sec. 3.3.4 and 4.3.4)
  - Questionnaire visualization tool (displays questionnaire PIs): `Questionnaire_visualization.exe`
  - Psychophysiological visualization tool (displays physiological signals and psychophysiological PIs): `Psychophysiological_visualization.exe`

### 3 Questionnaire data software

#### 3.1 EXPERIENCE questionnaire

##### 3.1.1 Structure and administration

The multifactorial EQ was developed to assess lower limb exoskeleton during treadmill rehabilitation and overground rehabilitation scenarios. The EQ layout is established based on the two selected applications: a set of general purpose items (General Rehabilitation Exoskeleton, GRE) is merged to application-specific items (TRE or ORE).

We identified the relevant Factors for the development of the questionnaire by reviewing the literature and by identifying psychological theories on technology acceptance and usability-quality models suitable to assess user experience during the use of rehabilitation and assistive lower limb exoskeletons. These models and theories have been applied in a wide variety of domains to understand and predict users' behavior and adoption of new technologies. Moreover, they have been demonstrated to be the theoretical ground needed to build evaluation processes by taking into account the totality of aspects involved in the user experience. In the revision process, we also included questionnaires available in the fields of robotic neurorehabilitation. We finally selected the Factors that affect (or could be influenced by) user experience during exoskeletons usage. In particular, we identified 16 Sub-Factors grouped in 4 Factors: Usability, Acceptability, Perceptibility, and Functionality (Table 1). The definition of the current items of the EQ originates from a drafting procedure and the subsequent selection: the objective of these procedures was to develop simple and direct questions, to increase their understanding by the users. Therefore, the items were selected following a review by a panel of experts and through Focus Groups (FGs). Two different FGs to collect feedback on the developed EQ have been appointed. FG1 involved end-users, SCI and stroke subjects with previous experience in the use of exoskeletons (either commercial systems or research prototypes). FG2 involved experts chosen among medical doctors (physiatrists and neurologists), psychologists, bioengineers, physical therapists and philosophers.

Table 1: Factors and Sub-Factors of the EQ.

Usability	Acceptability	Perceptibility	Functionality
Effectiveness ES	Attitude towards Technology AT	Embodiment and Ownership EO	Learnability LY
Efficiency EY	Self-Efficacy SE	Agency AG	Flexibility FY
Satisfaction SN	Motivation MN	Emotion and Attachment EA	Robustness and Reliability RR
	Comfort CT	Health and Quality of Life HQ	Workload WD
	Safety SY		

Each of the Sub-Factors includes a variable number of items, depending on its complexity (Table 2). 115 general purpose items (GRE), shared between the two applications, are merged to application-specific (TRE or ORE) items. Overall, TRE questionnaire consists of 124 items, while ORE questionnaire consists of 132 items.

Table 2: EQ items distribution.

FACTOR	SUB-FACTOR	ITEMS		
		GENERAL ITEMS	APPLICATION-SPECIFIC ITEMS	
		GENERAL REHAB EXO	TREADMILL REHAB EXO	OVERGROUND REHAB EXO
USABILITY	UY	GRE	TRE	ORE
		I01 – I05	–	I01
		I01 – I05	–	–
ACCEPTABILITY	AY	I01 – I06	I01 – I03	I01, I02
		I01 – I08	–	–
		I01 – I07	–	–
		I01 – I06	–	–
		I01 – I06	I01	I01, I02
PERCEPTIBILITY	PY	I01 – I05	I01	I01, I02
		I01 – I04	–	–
		I01 – I05	I01	I01 – I04
		I01 – I08	–	I01
FUNCTIONALITY	FY	I01 – I11	–	–
		I01 – I07	I01	I01 – I04
		I01 – I05	I01	–
		I01 – I05	–	–
		I01 – I06	I01	I01

Each item has to be rated on a 7-point Likert-type scale (from 1 "I strongly disagree" to 7 "I strongly agree").

Some items are reversed and consequently also the score is adapted (e.g. For the reversed item "The exoskeleton is useless." score of 5 is mapped in a new reversed score of 7+1-5=3).

The EQ includes a control subscale (consistency scale) with the aim to evaluate the reliability of the user in providing consistent scores to very similar items. To this aim control items, i.e. rephrased versions of already administered items, are hidden within the EQ. Scores provided to similar items can be compared and discrepancies might indicate that subjects' answer have limited reliability.

### 3.1.2 Items encoding

To uniquely identify each item of the EQ, the following encoding method has been adopted: two characters (letters) identify the Factor and the Sub-Factor, three characters (letters) identify the application, and three characters (letter I and one two-digit number) identify the item (Figure 4).



Figure 4: EQ items encoding structure.

*Example:* The code UY.ES.GRE.I01 refers to first (I01) item, in the application GRE (General Rehabilitation Exoskeleton), for the Sub-Factor ES (Effectiveness) belonging to the Factor UY (Usability).

## 3.2 Questionnaire data collection software

To collect EQ scores a Graphical User Interface (GUI) was developed in Matlab 2020a (The Mathworks Inc.). The GUI is an executable file and it includes mainly the following sections:

- Opening
- Input method (*options*: Create New Subject or Retrieve existing subject)
- Subject personal data entry
- Subject clinical data entry
- Instructions for the subject
- Administration mode selection (*options*: predefined administration or random administration)
- Application selection (*options*: treadmill or overground)
- Factor/Sub-Factors definitions
- Questionnaire rating collection
- Sub-Factors pairwise comparison collection
- Training evaluation
- Closing

Details will be reported in the following sections.

### 3.2.1 Software installation and run

The software requires the installation of [Matlab Runtime 9.8](#) to be downloaded from the Mathworks Inc. website. After this step, the file `Questionnaire_software.exe` has to be launched to run the software.

### 3.2.2 Software use

The instructions to use the software are reported below.

1. Open the folder 'Questionnaire\_software' and run the file `Questionnaire_software.exe` to open the GUI.
2. Click on the "Next" button to start the administration of the questionnaire
3. Select the input method (Figure 5) and click on the "Next" button to continue or on the "Back" button to return to the previous sheet (the "Back" button will be present in each sheet from here on).
  - *Create New Subject*: it allows to register a new subject; two options are included: *insert subject ID* (identification number for each subject) and *run number* (session number).
  - *Retrieve existing subject*: it allows to upload personal information of a subject who has already performed a session of the EQ (run 1), to use it for the second session (run 2). Select the folder "EXPERIENCE\_DATA", select the "Overground" or "Treadmill" folder, select the "Name\_Surname" folder.

Select input method

Create new subject      Subject ID:       Run number:

Retrieve existing subject

Figure 5: Select input method sheet.

4. Fill in the subject *Personal Data* sheet (Figure 6) and click on the "Next" button to continue; the default value is always set on "Healthy".

## Personal Data

Name:

Surname:

Age:

Gender:  M  F

Clinical Status:  Healthy  Stroke  SCI  Other

Employment:

Years of education:

Figure 6: Personal Data sheet.

5. Fill in the *Clinical Assessment* sheet depending on subject clinical status and click on the "Next" button to continue (optional information). Different sheets are available:

- Healthy subject (Figure 7)
- Stroke subject (Figure 8)
- SCI subject (Figure 9)

**Clinical Assessment:**

Beck Depression Inventory (BDI):

Anxiety Sensitivity Index (ASI):

Mini-Mental State Examination (MMSE):

**Back** **Next**

Figure 7: Healthy subject assessment sheet.

**Clinical Assessment:**

Type of stroke event:	<input type="radio"/> Ischemic	<input checked="" type="radio"/> Haemorrhagic
Date of the event:	<input type="text"/> / <input type="text"/> / <input type="text"/>	
Beck Depression Inventory (BDI):	<input type="text"/>	
Beck Anxiety Inventory (BAI):	<input type="text"/>	
Mini-Mental State Examination (MMSE):	<input type="text"/>	
Barthel Index (BI):	<input type="text"/>	
Functional Ambulation Categories (FAC):	<input type="text"/>	

[Back](#)      [Next](#)

Figure 8: Stroke subject assessment sheet.

**Clinical Assessment:**

Injury Level:	<input type="text"/>
AIS Impairment Scale:	<input type="text"/>
Date of the event:	<input type="text"/> / <input type="text"/> / <input type="text"/>
MAS (Modified Ashworth Scale):	<input type="text"/>
MMS (Manual Muscle Test):	<input type="text"/>
Beck Depression Inventory (BDI):	<input type="text"/>
Beck Anxiety Inventory (BAI):	<input type="text"/>
Mini-Mental State Examination (MMSE):	<input type="text"/>
Walking Index for Spinal Cord Injury (WISCI):	<input type="text"/>
Spinal Cord Independence Measure (SCIM):	<input type="text"/>

[Back](#)      [Next](#)

Figure 9: SCI subject assessment sheet.

6. Read the instructions to the subject and click on the "Next" button to continue.
7. Select the sequence of administration (Figure 10) and click on the "Next" button to continue
  - *Predefined*: the questionnaire will be administered in a predetermined order.
  - *Random*: the questionnaire will be administered by proposing the Factors, and the Sub-Factors within them, in a random order; the default value is always set on "Random".

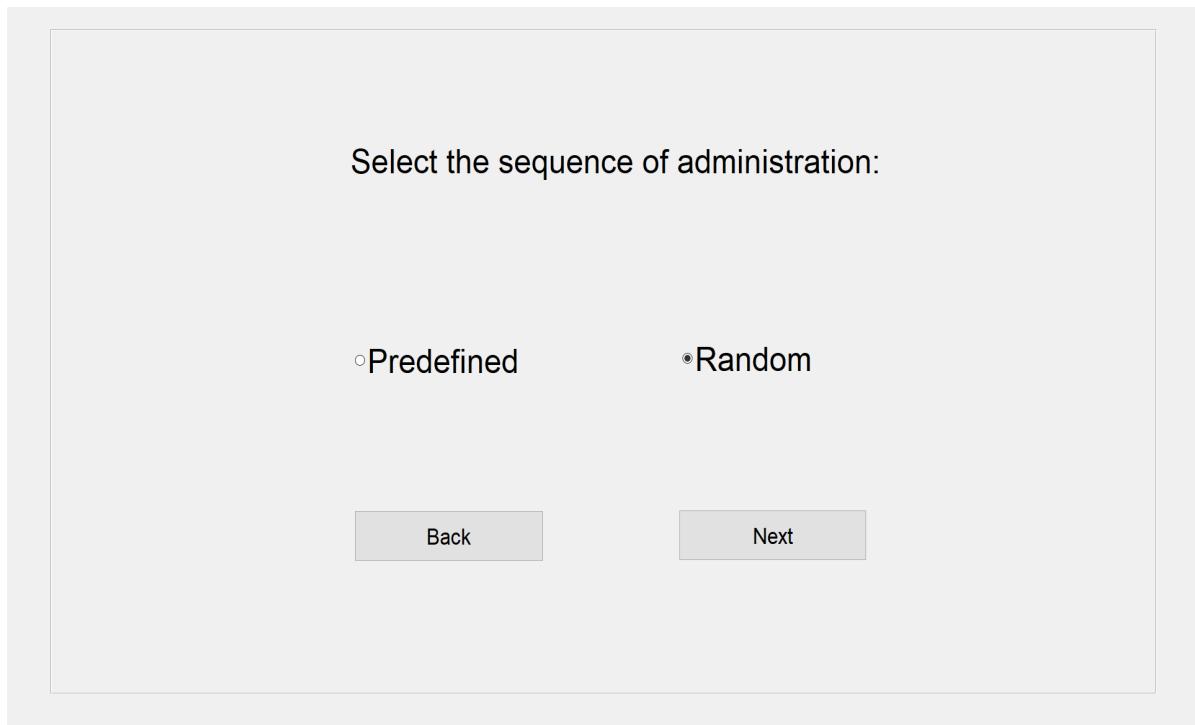


Figure 10: Sequence of administration sheet.

8. Select the experimental condition (Treadmill or Overground), insert the name of the exoskeleton (optional information) and click on the "Next" button to continue.
9. Read the Factors and Sub-Factors' definitions to the subject (Figure 11) and click on the "Next" button to continue.

FACTOR:		Back	Next
<b>USABILITY</b>	The first factor is USABILITY, which indicates how useful the exoskeleton is for you to carry out the task, if it is convenient and if its use satisfies you. It therefore answers to the question: "Is it useful to me?"		
This factor is divided into Effectiveness, Efficiency and Satisfaction.			
<b>SUBFACTORS:</b>			
<b>Effectiveness</b>	It describes whether you, together with the exoskeleton, can achieve the established goals. It therefore answers to the question "Is this useful for me to achieve my goals?"		
<b>Efficiency</b>	It measures the possibility to reach a goal by spending the right amount of resources, that is measuring if it is possible to you to get the maximum output with minimum effort. It therefore answers to the question "Is it useful for me to achieve my goals in a cost-effective way?"		
<b>Satisfaction</b>	It measures how much you positively evaluate the characteristics of the exoskeleton and the services connected to the received assistance. It therefore answers to the question "Does it satisfy me in all its parts and functions?"		

Figure 11: Factors and Sub-Factors' definitions sheet.

10. Fill in the questionnaire with the subject's rating (Figure 12) and click on the "Next" button to continue (repeat for all the Sub-Factor belonging to each Factor); the default value is always set on "4".

**PERCEPTIBILITY**

**Agency**

It evaluates how much you feel to have control over your movements, while walking with the exoskeleton.  
It therefore answers to the question "Do I feel the control over my body (over my legs), and over my actions, when I walk with the exoskeleton?"

	Completely Disagree	1	2	3	4	5	6	7	Completely Agree
PY.AG.GRE.I02 - I like how the exoskeleton fits my body	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
PY.AG.TRE.I01 - I feel able to control my performance thanks to the feedback on the screen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
PY.AG.GRE.I03 - While walking with the exoskeleton, sometimes it seems to me I am performing inappropriate, uncontrolled or uncoordinated movements	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
PY.EO.GRE.I01 - When I walk with the exoskeleton I feel that my legs are light	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
PY.AG.GRE.I01 - When I walk with the exoskeleton I feel control over my legs and my whole body	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
PY.AG.GRE.I05 - When I walk with the exoskeleton, I can focus on my steps and the movements to be made	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
PY.AG.GRE.I04 - While walking with the exoskeleton, it seems to me I am not controlling my movements	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	

**Back** **Next**

Figure 12: Subject's questionnaire rating sheet.

11. Fill in the *Pairwise Comparison* sheet (Figure 13) and click on the "Next" button to continue (repeat at the end of every Factor); the default value is always set on the Sub-Factor on the right side.

**Usability**

**Definition**

Now we ask you to evaluate your experience in the different aspects of the questionnaire, comparing them with each other: choose which of the two sub-factors was the most important for your experience with the exoskeleton. For example, if you think of any device you use, it is more important its robustness or the workload it requires during the use? Which aspect matters the most? And therefore, during the experience with the exoskeleton, which one of the two sub-factors was more important? The objective of the evaluation you are about to carry out is to quantify the importance that each aspect has had in the experience you have lived. Please consider your choices carefully, referring to your experience and the scores you gave in answering the questionnaire.

<input type="radio"/> Effectiveness	<input checked="" type="radio"/> Efficiency
<input type="radio"/> Effectiveness	<input checked="" type="radio"/> Satisfaction
<input type="radio"/> Efficiency	<input checked="" type="radio"/> Satisfaction

**Back** **Next**

Figure 13: Pairwise comparison sheet.

12. Fill in the *Training* evaluation sheet (Figure 14) to assess the user's previous experience with the exoskeleton, and his/her satisfaction with the information received about the training and the questionnaire. Insert the task and/or possible notes (optional information) and click on the "Next" button to continue.

## Training evaluation

Previous experience with the exoskeleton

Completely Inexpert	Completely Expert
<input type="radio"/> 1 <input type="radio"/> 2 <input type="radio"/> 3 <input checked="" type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7	

Are you satisfied with the information received about the rehabilitation training with the exoskeleton, the task, and the established goals?

Completely Unsatisfied	Completely Satisfied
<input type="radio"/> 1 <input type="radio"/> 2 <input type="radio"/> 3 <input checked="" type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7	

Are you satisfied with the information received about the aspects of the questionnaire, the items, and how to answer them?

Completely Unsatisfied	Completely Satisfied
<input type="radio"/> 1 <input type="radio"/> 2 <input type="radio"/> 3 <input checked="" type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7	

Task:

Notes:

**Back** **Next**

Figure 14: Training evaluation sheet.

13. Click on the "End" button to end the questionnaire in the final sheet (Figure 15).

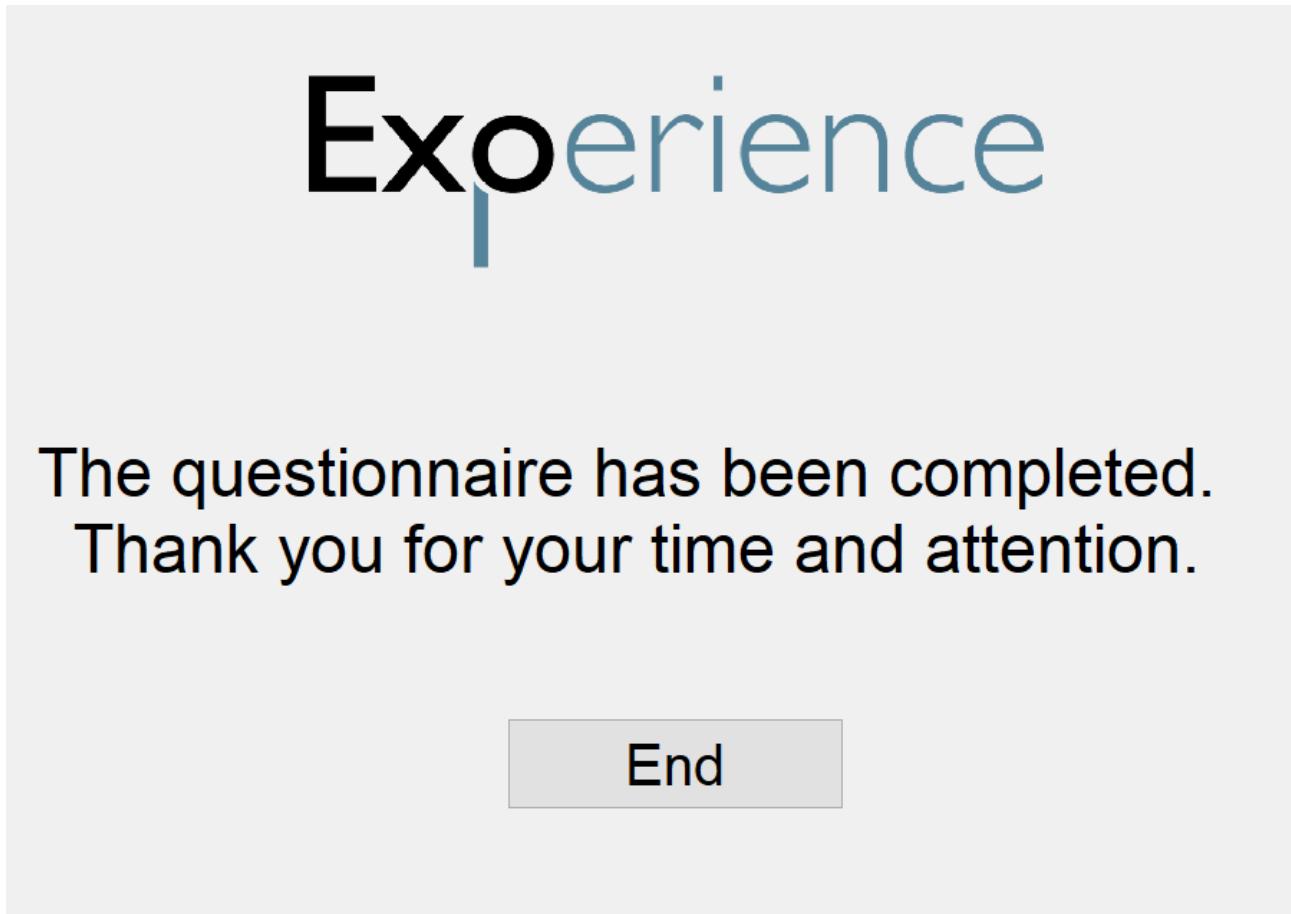


Figure 15: Final sheet of the EQ.

14. At the end of the administration, the results will be automatically saved in a parent folder named 'EXPERIENCE\_DATA' and based on the experimental condition, the subject folder will be stored in a 'Treadmill' or 'Overground' subfolder. The subject folder tree will be organized as reported in Figure 16.

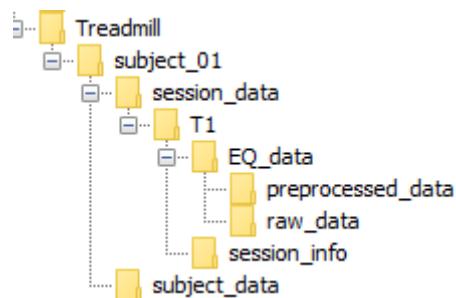


Figure 16: Organization of the stored subject folder.

In particular, we have two main subfolders:

- **session\_data:** includes data from all the administered sessions (in the example is reported the case of 'T1', i.e. run1)
  - T1 (each session folder) contains two folders:
    - 'EQ\_data' with preprocessed and raw data files

- 'session\_info' containing the questionnaire administration date
- **subject\_data:** contains a Matlab .mat structure with all the subject anographical and clinical data.

### 3.3 Questionnaire performance indicators

#### 3.3.1 PIs definition

The questionnaire outputs 5 different PIs.

1. **PI\_usability:** it is defined as the extent to which the exoskeleton can be used by the users to achieve specified goals with effectiveness, efficiency, and satisfaction in this specified context of use. High value of this PI indicates that the robot is highly usable.

It is automatically stored as a labelled matrix of four values respecting the structure below.

value: [['effectiveness', 'efficiency', 'satisfaction', 'usability'], [value, value, value, value]]

2. **PI\_acceptability:** it relates to how the users perceive robots when interacting directly with them and how much you would be willing to introduce it into your everyday life. High value of this PI indicates that the robot is highly acceptable.

The labelled matrix associated to this PI is reported below:

value: [['attitude towards technology', 'self-efficacy', 'motivation', 'comfort', 'safety', 'acceptability'], [value, value, value, value, value, value]]

3. **PI\_perceptibility:** it evaluates the effects and influences that walking with the exoskeleton has on your emotions, perceptions, and quality of life. High value of this PI indicates that the robot positively influences emotion, perception, and quality of life.

The labelled matrix associated to this PI is reported below:

value: [['embodiment and ownership', 'agency', 'emotion and attachment', 'health and quality of life', 'perceptibility'], [value, value, value, value, value]]

4. **PI\_functionality:** it measures the perception of the characteristics of the exoskeleton in terms of ease of learning, flexibility of interaction, reliability, and workload. High value of this PI indicates positive features of the robot in terms of analyzed aspects.

The labelled matrix associated to this PI is reported below:

value: [['learnability', 'flexibility', 'robustness and reliability', 'workload', 'functionality'], [value, value, value, value, value]]

5. **PI\_experience:** it measures the global characteristics of the subject experiencing the exoskeleton in terms of usability, acceptability, perceptibility, and functionality. The consistency within this PI indicates the reliability of the subject in providing similar scores to similar items within the questionnaire. High value of this PI indicates positive features of the robot in terms of analyzed aspects.

The labelled matrix associated to this PI is reported below:

value: [['experience', 'consistency'], [value, value]]

#### 3.3.2 PIs calculation

The calculation of PIs is based on a three-level scoring:

- *Sub-Factor level.* Each Sub-Factor score ( $ss$ ) is calculated as the average among the related item scores ( $is$ ):

$$ss = \frac{1}{N_i} \sum_{k=1}^{N_i} i s_k$$

being  $N_i$  the total number of items belonging to each Sub-Factor.

- *Factor level*. Each Factor score ( $fs$ ) is calculated as the weighted average among the related Sub-Factor scores ( $ss$ ):

$$fs = \frac{2}{N_s(N_s - 1)} \sum_{k=1}^{N_s} w_k ss_k$$

being  $N_s$  the total number of Sub-Factors belonging to each Factor. The weights  $w_k$  (with  $k = 1, \dots, N_s$ ) are derived from the comparison between pairs of Sub-Factors (pairwise comparison) administered to the subject under testing. Sub-Factors are sorted based on the number of collected preferences so that the weights are consequently assigned. This method is used to calculate PIs from 1 to 4.

- *EQ level*. The overall questionnaire score<sup>2</sup> ( $qs$ ) is calculated as the average among the four Factor scores:

$$qs = \frac{1}{N_f} \sum_{k=1}^{N_f} fs_k$$

being  $N_f$  the total number of Factors. This method is used to calculate PI 5.

The computation of the user's consistency is based on the difference between the scores assigned to two similar items (the original item included in the EQ and the control rephrased item hidden within it). This difference will be indicated as *control item discrepancy*. A total of 16 control items has been included. An item and its control are considered to be scored in a consistent way if the *control item discrepancy* is in the range [-1, 1]. A higher *control item discrepancy* causes a proportional decrease in the total consistency score (maximum 100%).

### 3.3.3 PIs input data files

The administration and data analysis of the EQ entails the use of 2 files:

1. *Factor Data File*: a .csv file containing the answers to each of the questions asked within the Factor and the pairwise comparison among Sub-Factors. It is a two-columns file (as reported in Table 3), with one column for the item codes and one for the scores.

Table 3: Example of the Factor Data File.

itemID	answer
AY.AT.GRE.I01	[1,7]
AY.C01	0-1

The administration order is implicitly encoded in the row order.

2. *Factor Metadata File*: a .csv file named "questionnaire\_Experience" that includes information to interpret the *Factor Data File* with specification of each question of the questionnaire (Table 4).

---

<sup>2</sup> The calculation of this score is still under discussion.

Table 4: Example of the Factor Metadata File.

itemID	type	options	text	answer_unit	Control
AY.AT.GRE.I01	likert, reverse likert	<code>[[1, "I strongly disagree"], [2, "I disagree"], [3, "I slightly disagree"], [4, "Neutral"], [5, "I slightly agree"], [6, "I agree"], [7, "I strongly agree"]]</code>	question		boolean
AY.C01	boolean		pairwise comparison	boolean	

The content of the *Factor Data File* changes according to the data collected during the experiment while the content of the *Factor Metadata File* is pre-set and permanent.

Both files are compliant with the [EUROBENCH data format](#).

### 3.3.4 Questionnaire PIs visualization software

In order to visualize the questionnaire PIs, a GUI was developed in Matlab 2020a (The Mathworks Inc.).

The instructions to use the visualization tool are reported below:

1. Open the folder Questionnaire visualization and run the file `Questionnaire_visualization.exe` to start the application.
2. Enter the run number and press the “Select subject folder” button to retrieve the existing subject folder (Figure 17).

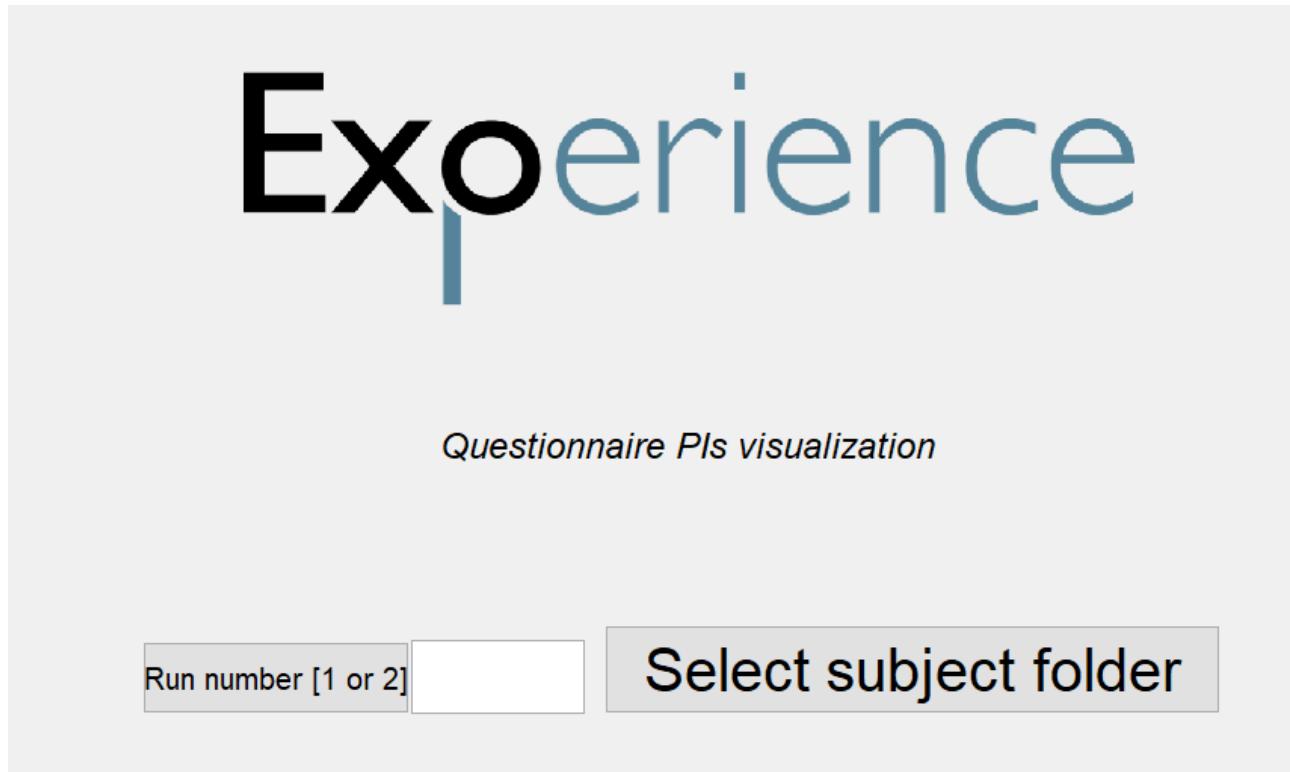


Figure 17: Questionnaire PIs visualization sheet.

- Once selected the desired subject folder, a new sheet will show a brief report of the subject data and all the computed PIs (Figure 18)

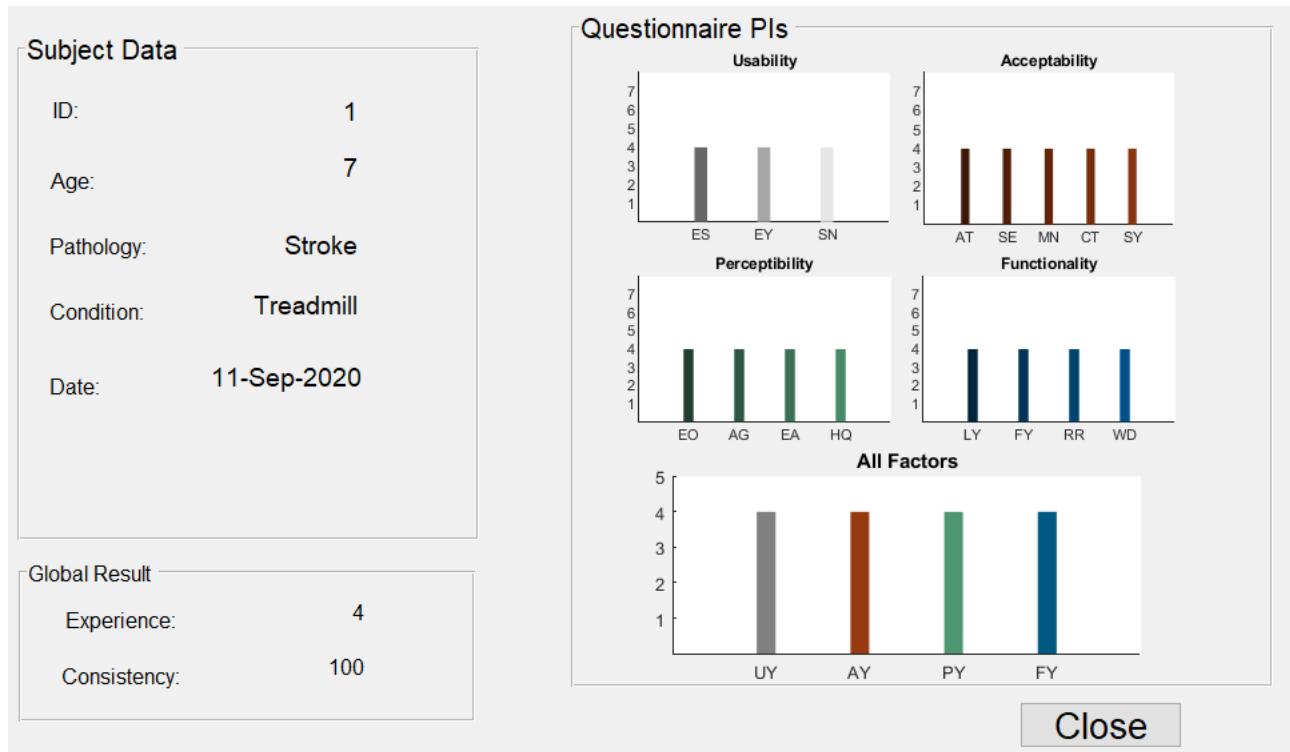


Figure 18: Sheet containing Subject Data, Questionnaire PIs and Global Result.

## 4 Psychophysiological data software

### 4.1 Physiological data collection software

To record the physiological signals, a GUI was developed in Matlab 2018b (The Mathworks Inc.). The GUI is an executable (`Physiological_software.exe`) file and it allows the connection and synchronization of the sensors.

#### 4.1.1 Software installation and run

The software requires the installation of [Matlab Runtime 9.8](#) to be downloaded from the Mathworks Inc. website. A Bluetooth connection must be established between sensors and the device.

#### 4.1.2 Software use

The instructions to use the software are reported below.

1. Run the file `Physiological_software.exe` to open the GUI.
2. Click on the “Connect BioHarness” (Figure 19) button to connect the BioHarness sensor. When the button turns green, the sensor is connected.

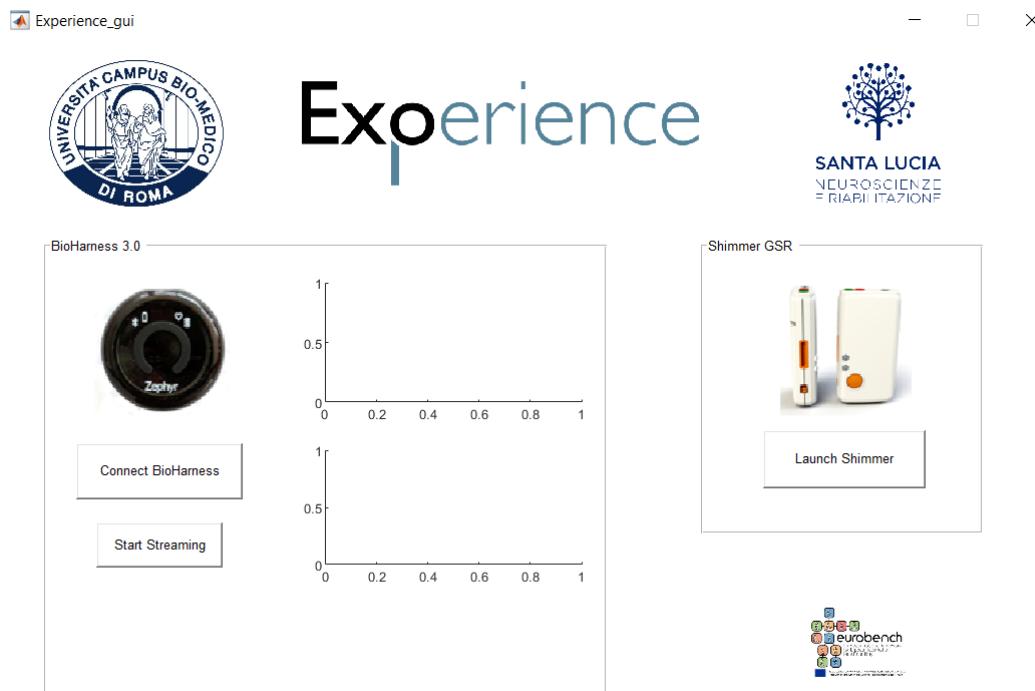


Figure 19: GUI for sensors connection.

3. Click on the “Start Streaming” button to display the ECG signal in the upper plot and the respiratory rate in the lower plot (Figure 20).



# Experienc

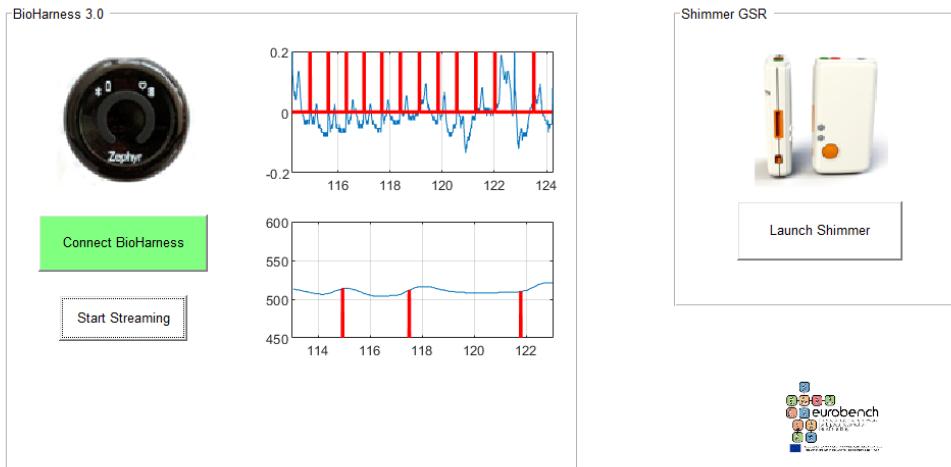


Figure 20: Streaming of ECG and RR.

- Click on the “Launch Shimmer” button to open the Shimmer sensor interface (Figure 21).

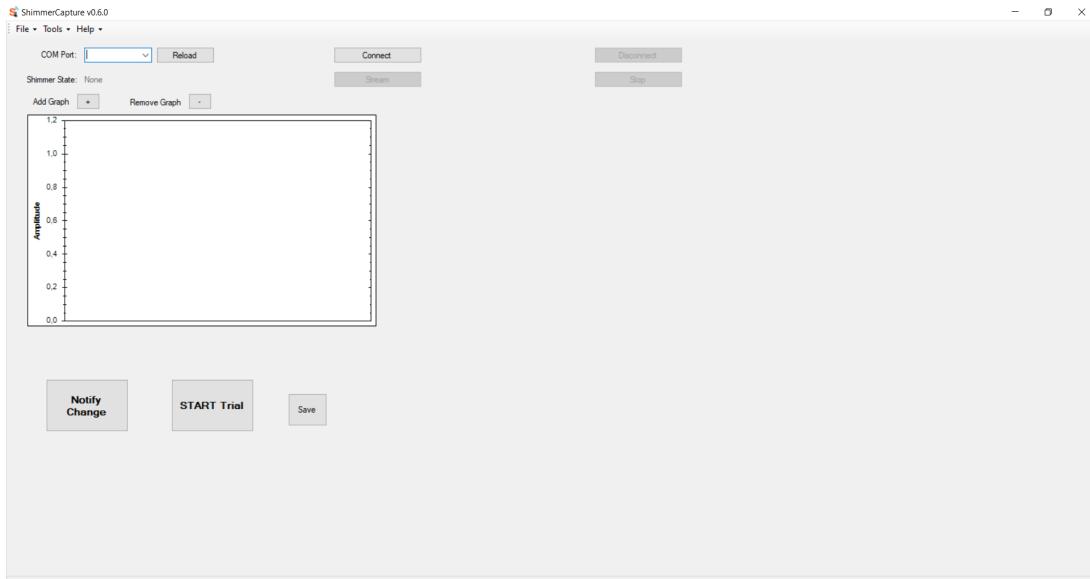


Figure 21: Shimmer interface.

- Search for the right COM Port from the drop-down list and click the “Connect” button. If the right port has been selected the button turns green.
- Click on the “Stream” button and tick the “GSR RAW” box to display the GSR signal in the plot (Figure 22).
- Click on the “START Trial” button to start one of the three phases of the experiment.
- Click on the pop-up “STOP Trial” button to end the measurement phase.

9. To notify the presence of changes in therapy, such as the addition of rehabilitation games or biofeedback or possible changes in the exoskeleton settings, click on the "Notify Change" button.

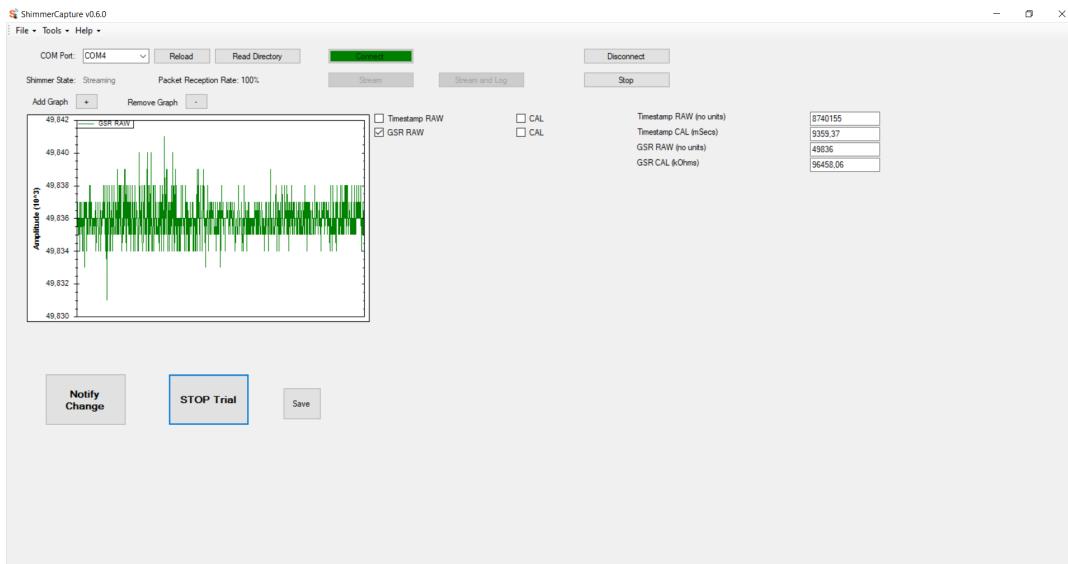


Figure 22: Streaming of GSR.

10. Click on the "Save" button to end the recording.

## 4.2 Pre-processing software

The Psychophysiological data software produces the following raw data:

- hr.txt
- hrv.txt
- rr.txt
- gsr.txt
- trigger.txt
- ecg\_raw.dat

In the `Preprocessing_algorithm.m`, starting from raw .txt data, .csv files are created. Using the trigger data, the signals are cut and 3 .csv files are obtained, one for each measurement phase (sit, stand and walk), both for physiological and physiological\_ecg data.

## 4.3 Psychophysiological performance indicators

### 4.3.1 PIs definition

The four Psychophysiological PIs include:

1. *PI\_stress*: it is defined as a state of mental or emotional strain caused by adverse circumstances. High value of this PI indicates that the robot use is stressful.
2. *PI\_energy\_expenditure*: it is the amount of energy that is needed to carry out physical functions. High value of this PI indicates that the robot use requires high effort.
3. *PI\_attention*: it refers to the degree to which the user is consciously and continuously involved in the task. High value of this PI indicates that the robot use requires high attention.
4. *PI\_fatigue*: It can be described as a type of distress generally conditioned by the exhaustion of one's muscles due to the execution of a task. High value of this PI indicates that the robot use induces fatigue.

### 4.3.2 PIs calculation

The power distribution in the Low-Frequency (LF) band (0.04-0.15 Hz) was extracted from the ECG data (Shaffer). Two components were extracted from the GSR signal: Skin Conductance Level (SCL), i.e. the tonic level in the absence of any particular environmental event, and the Skin Conductance Response (SCR), i.e. an event-dependent, phasic and highly responsive parameter.

A method based on Fuzzy logic approach was implemented for the extraction of the four mentioned PI indicators: stress, fatigue, energy expenditure and attention. The physiological signals of the walking phase were considered only for the last 15-min recording and were normalized with respect to the data collected during the sit phase. The employed Fuzzy logic method included 6 inputs (HR, RMSSD, RR, SCR, SCL and LF) and 4 outputs (PIs). For each physiological signal, the membership functions were constructed by taking into account the total number of occurrences in all the collected data. In particular, three levels for the model inputs and outputs (low, medium and high) were introduced. The IF/THEN rules were defined based on trends of variation of physiological signals retrieved from a careful analysis of the scientific literature. These rules combine all the input physiological data to finally estimate the four PIs.

### 4.3.3 PIs input data files

The analysis of physiological data involves the use of 2 files (for each registration's phase) because the ECG is recorded with a different frequency (250 Hz) respect to the other parameters (25 Hz):

- *physiological*: a .csv file containing the recorded values for each physiological parameter. It is a five-columns file: the first one for timestamp and the other four for parameters.

<b>time</b> [sec]	<b>hr</b> [bpm]	<b>hrv</b> [sec]	<b>rr</b> [bpm]	<b>gsr</b> [mS]
-------------------	-----------------	------------------	-----------------	-----------------

- *physiological\_ecg*: it is a two-columns .csv file: the first one for timestamp and the second one for the recorded values of ecg.

<b>time</b> [sec]	<b>ecg</b> [mV]
-------------------	-----------------

Both files are compliant with the [EUROBENCH data format](#).

### 4.3.4 Psychophysiological PIs visualization software

To display the physiological signals and the Psychophysiological PIs, a GUI was developed in Matlab 2020a (The Mathworks Inc.).

The instructions to use the software are reported below.

4. Run the file `Psychophysiological_visualization.exe` to open the GUI.
5. Enter the subject and run number and press the "Load data" button to load the data (Figure 23)

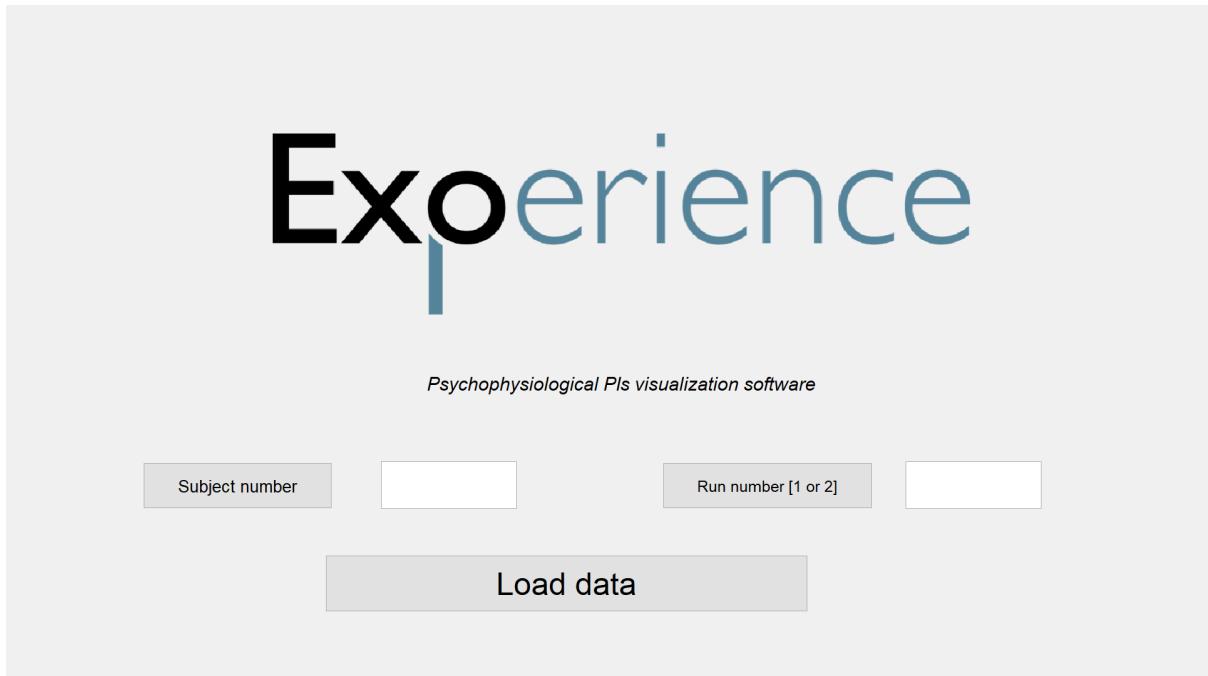


Figure 23: Psychophysiological PIs visualization sheet.

15. Select the parameters to be displayed (Figure 24) or click on the “Back” button to return to the previous sheet (the “Back” button will be present in each sheet from here on).

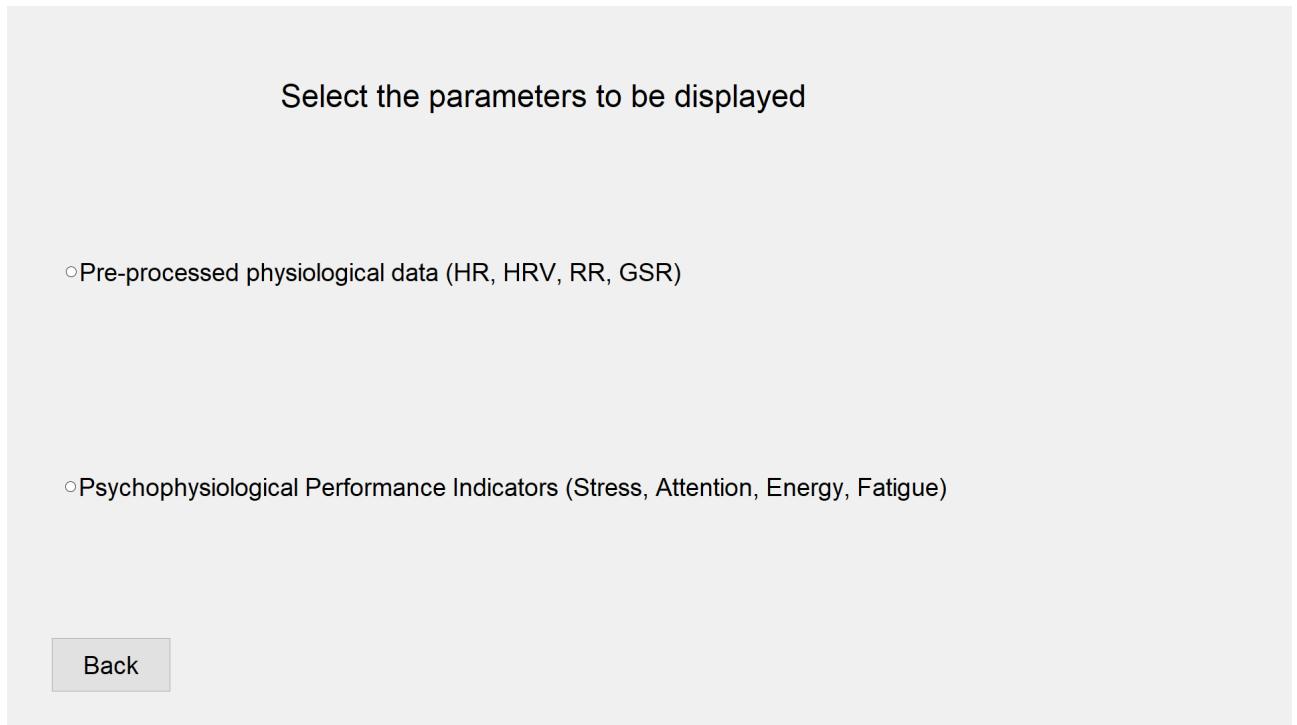


Figure 24: Selection sheet between Pre-processed physiological data and Psychophysiological Performance Indicators.

6. In the sheet in Figure 25 are shown the number and the run of the subject and the respective physiological parameters.

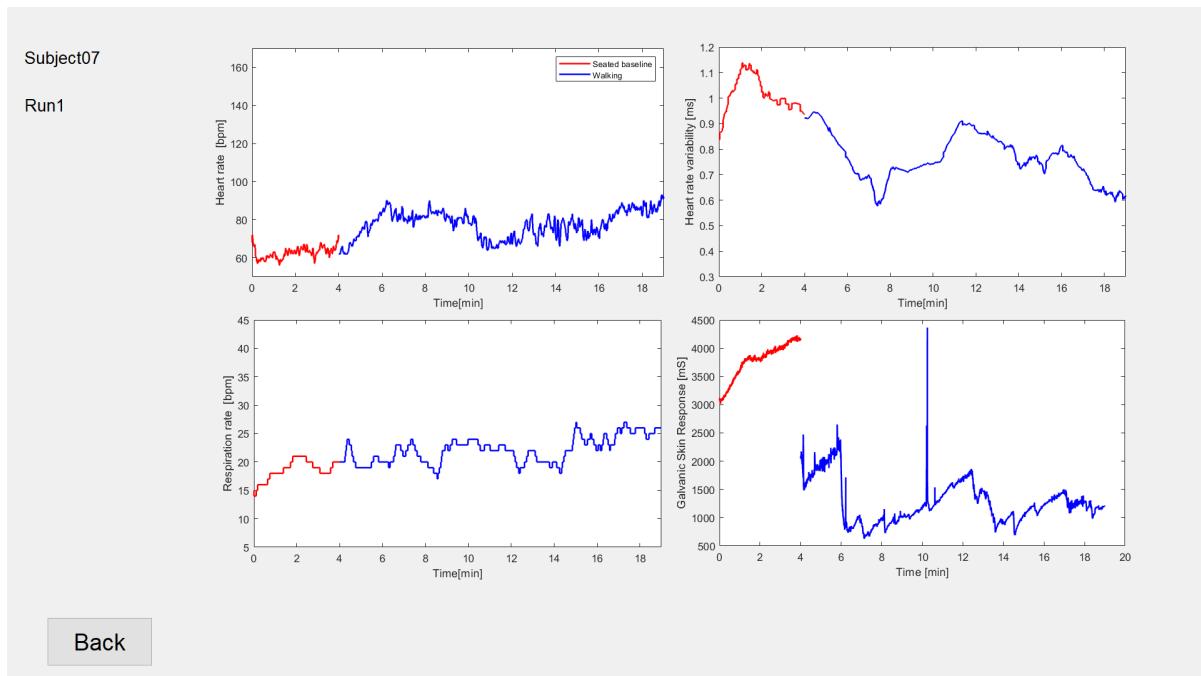


Figure 25: Sheet containing Subject Data and Physiological signals.

7. In the sheet in Figure 26 are shown the number and the run of the subject and the related Psychophysiological PIs. Click on the "End" button to end the software.

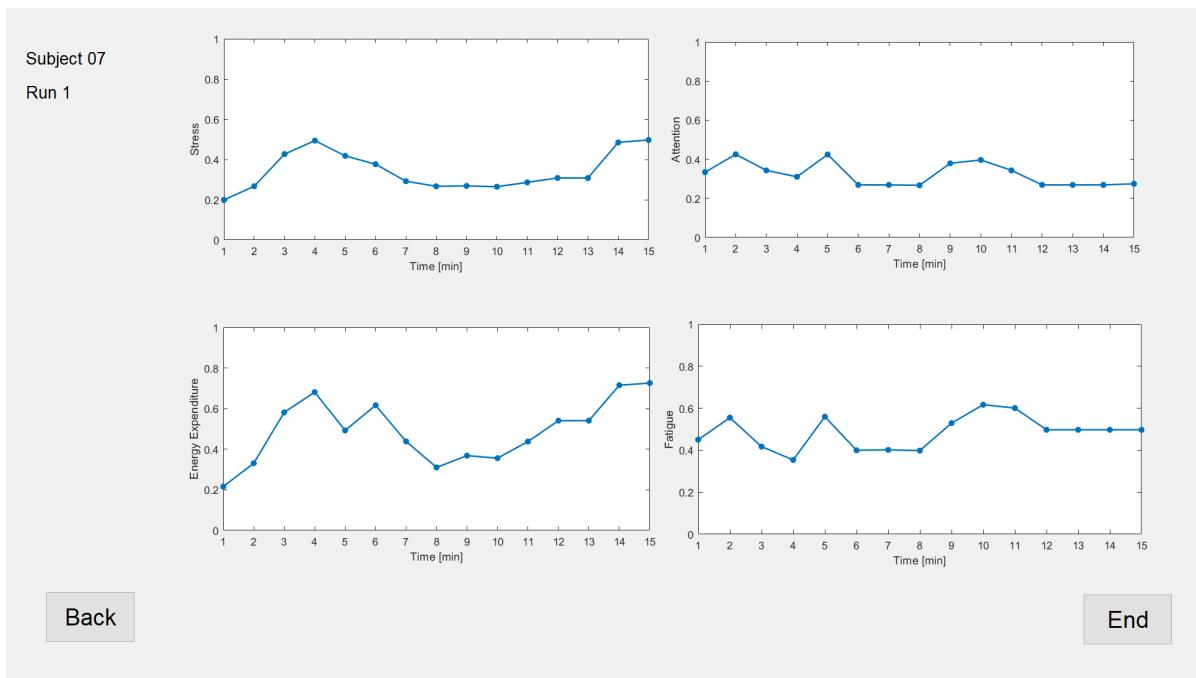


Figure 26: Sheet containing Subject Data and Psychophysiological PIs.

## 5 Dataset

### 5.1 Subjects overview

22 subjects were recruited for the experiments (Table 5: Data of recruited subjects). Recruitment criteria were defined within the experimental protocol approved by the Ethics Committee of FSL (protocol number CE/PROG 746).

Table 5: Data of recruited subjects.

Subject	Clinical State	Sex	Age	Education Level	Exoskeleton
1	SCI	F	35	18	Lokomat
2	Stroke	M	53	13	Lokomat
3	SCI	M	65	13	Lokomat
4	Stroke	F	78	5	Lokomat
5	Healthy	F	26	16	Lokomat
6	Healthy	F	58	18	Lokomat
7	Healthy	M	27	18	Lokomat
8	Healthy	F	26	16	Lokomat
9	Stroke	M	85	5	Lokomat
10	Healthy	M	26	16	Lokomat
11	Healthy	F	25	16	Lokomat
12	Healthy	F	23	16	Lokomat
13	SCI	M	70	13	Lokomat
14	SCI	M	57	16	Ekso
15	Stroke	M	35	16	Ekso
16	Healthy	F	25	16	Ekso
17	Healthy	F	23	16	Ekso
18	Healthy	F	58	18	Ekso
19	SCI	M	32	12	Ekso
20	SCI	M	29	13	Ekso
21	Healthy	M	26	13	Ekso
22	SCI	F	77	13	Lokomat

### 5.2 Collected data naming

To uniquely identify each physiological data recorded, the following encoding method has been adopted for the filename:

subject\_N\_run\_R\_part\_X\_K

where N is the number of the subject, R the number of the run (1 or 2), part\_X is the measurement phase (sit, stand or walk) and K is the measured signal (physiological or physiological\_ecg).

Similarly, in case of questionnaire data, the following encoding solution has been adopted:

subject\_N\_run\_R\_questionnaire\_Experience\_Factor

#### 5.2.1 Notes

In some recordings the walking phase does not last 15 minutes because the patient was not able to complete the rehabilitation therapy.

### 5.3 Testing dataset

A “testing dataset” was produced including real data collected on a representative healthy subject walking with the Ekso (Sub16) and Lokomat (Sub11) is reported.

## 6 Appendix A – Datasheet of Zephyr BioModule 3 sensor



**BioHarness 3 Medical Data Sheet**

### Zephyr BioHarness™ 3

#### PRODUCT DESCRIPTION

The BioHarness™ 3 is a compact physiological monitoring module. It is attached to a lightweight Smart Fabric strap or garment which incorporates ECG and Breathing detection sensors.

The BioHarness™ module can transmit physiological data or record it to internal memory.

#### FEATURES

- ▽ Bluetooth Connectivity to receiver or external sensors
- ▽ Heart Rate 25 – 240 BPM ( $\pm 1$  BPM)
- ▽ Breathing Rate 3 – 70 BPM ( $\pm 1$  BPM)
- ▽ Device Temperature 10 – 60°C ( $\pm 2$  °C)
- ▽ Position/posture  $\pm 180^\circ$  (Laying, standing)
- ▽ Activity in VMU (Stationary, walk, run)
- ▽ 3 axis Acceleration to 16g
- ▽ Red / Orange / Green subject status indication
- ▽ Transmit and/or Logging Modes
- ▽ EC38 Type 3
- ▽ 250Hz ECG Transmission & Logging
- ▽ 100Hz Accelerometer Logging
- ▽ USB connectivity for data download & charging
- ▽ Up to 500+ hours data storage
- ▽ Internal algorithms for
  - Estimated core temperature
  - Jump Test
  - Dash Test
  - Fall detection
  - Heart Rate Variability
  - Human Real Data

#### Company Information

Zephyr Technology

1 Annapolis St  
Suite 200  
Annapolis  
MD 21401

Tel: +1 (443) 569-3603  
Fax: +1 (443) 926-9402  
Email: sales@zephyranywhere.com  
[www.zephyr-technology.com](http://www.zephyr-technology.com)

*Data subject to change*

#### APPLICATIONS

- ▽ Biomechanical and physiological research
- ▽ Remote Patient Monitoring
- ▽ Physical status monitoring in real world situations

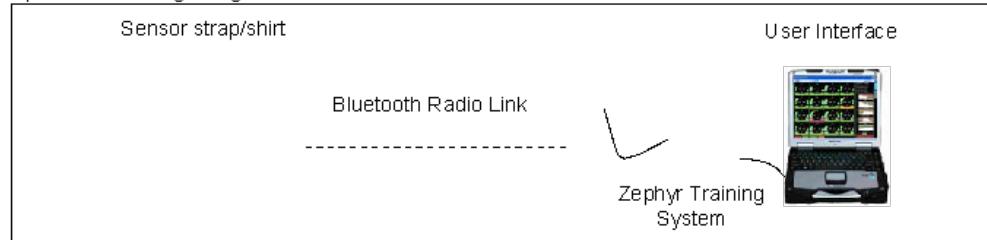
Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

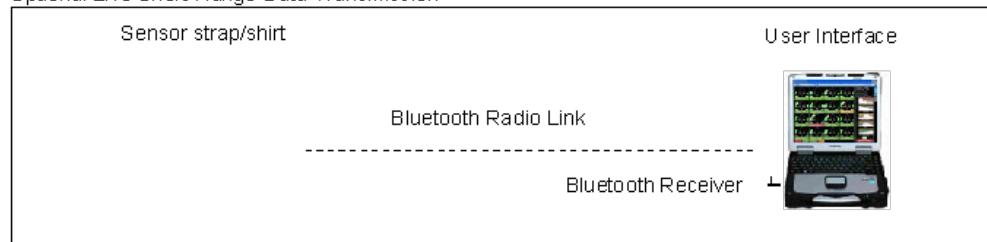
Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

***BioHarness 3 Medical Data Sheet***

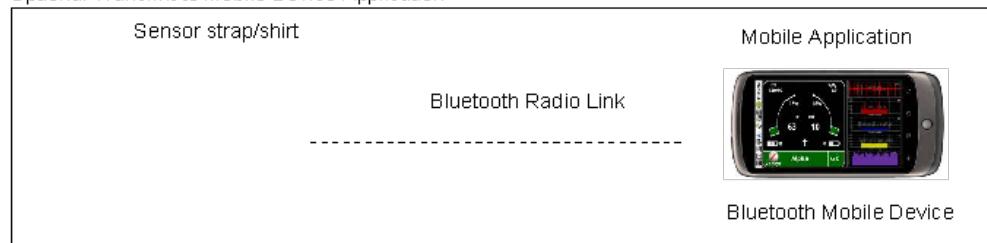
## Optional Live Long-Range Data Transmission



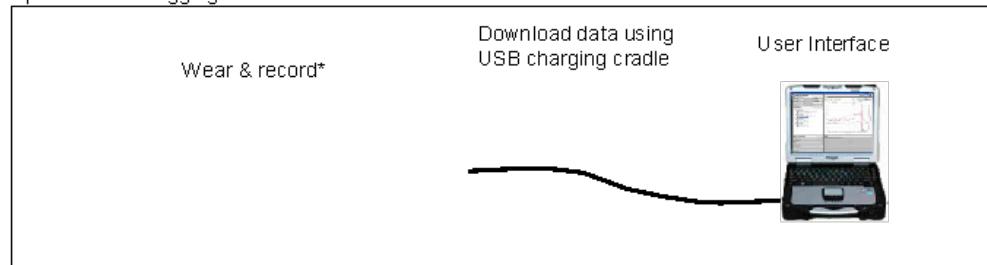
## Optional Live Short-Range Data Transmission



## Optional Transmit to Mobile Device Application



## Optional Data Logging



\*Device must be configured to log. Software needed for data import.

Page 2 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

**BioHarness 3 Medical Data Sheet**

**Specifications** (Unless otherwise stated: Temperature = 25 °C, Pressure = 1 ATM, Fresh battery, g = gravity units)

**Power Supply:** Internal Lithium cell, rechargeable via USB charging cradle or USB wall charger.

Parameter	Notes	Min	Typ.	Max	resolution	Unit
<b>General</b>						
Logging capacity	1		500+			hours
Power supply voltage	USB	4.5	5	5.5		V
Battery Life – Radio transmitting	2	12		24		hrs
Battery Life - Logging	3		35			hrs
Log Download Time	4	1		6		Min per hr of log
Charging Time			3			hrs
Storage	Between charges		6			months
Charging Cycles	5		300			Cycles
ECG Digital resolution	6	10		12		bits
<b>Heart Rate</b>						
ECG sensor sampling frequency			1000			Hz
Range	7	25	240	±1		BPM
R-R		250		1500		ms
Time to first lock	At 60 bpm		15	25		s
No Signal Response time	60 to 0 bpm		10			s
Input dynamic range		0.1		10		mV <sub>pp</sub>
ECG Amplitude	8	0.25		15		mV

**Operating Modes:**

- Active – device transmitting data + logging, if configured  
 Standby – device not transmitting but connectable + logging, if configured

**Notes:**

1. General Logging (Gen + ECG = 140hrs, Gen + Acceleration = 280hrs)
2. Min Period – after 180 charge cycles. Max Period – new battery
3. Software required for data download.
4. Min: General Log only. Max: Summary + Waveform
5. After 300 deep discharge/charge cycles the battery will retain a minimum of 80% of its original capacity.
6. 12 bit sampling. Transmit 10 bit, Log 12 bit.
7. Heart Rate Accuracy for defined activity levels: based on USARIEM\* guidelines

Accuracy (bpm) ±1	Activity Level Laboratory – ECG simulator	VMU	USARIEM % of time 100	Zephyr % of time 99	Max Deviation (bpm) 1
±2	Low activity (static)	< 0.2	99	99	5
±3	Moderate activity (walk/jog)	< 0.8	95	96	5
±3	High activity (run)	> 0.8	90	95	10

8. Accuracy greater of 100 µV or 10%

\*United States Army Research Institute of Environmental Medicine

Page 3 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

**BioHarness 3 Medical Data Sheet**

Parameter	Notes	Min.	Values Typ.	Max.	Acc'y	Unit
<b>Breathing Rate</b>						
Sampling frequency			25			Hz
Range	9	3	15	70	±1	BPM
No signal response time						s
Step change response time			15			s
<b>Device Temperature</b>						
Sampling frequency	10	10	1	60	±2	s °C
Stabilization Time			20			minutes
<b>Acceleration</b>						
Sampling Frequency		-16	100	+16		Hz g
Range (any axis)						Hz
Bandwidth			50			mg
Sensitivity			12			
<b>Activity</b>						
VMU (vector magnitude units)	11			16		g
Epoch			1			s
Bandwidth		0.06		9		Hz
Dynamic Range (any axis)		0.16		16		g
Sensitivity			10			mg
Noise			7.2			mg
<b>Posture</b>						
Reporting frequency			1			Hz
Dynamic Range	12	-180		+180		Degrees
Epoch			1			s
Sensitivity		8		1		Degrees

Recommended storage temperature 20°C

Notes:

9. Breathing Rate Accuracy for defined conditions: based on USARIEM\* guidelines

Accuracy (Bpm)	Condition (average every 15 seconds)	VMU	USARIEM % of time	Zephyr % of time	Max Deviation (bpm)
±2	Laboratory – breathing emulator		100		2
±3	Low activity (static)	< 0.2	95	75	5
±3	Moderate activity (walk/jog)	< 0.8	95	65	5
±5	High activity (run)	> 0.8	90	75	12
±5	Talking & breathing rate in range 6 – 25 bpm		100		

10. Min = device transmitting, Max = device logging

11. Vector Magnitude Units, 3 axis, sampled at 100 Hz, averaged to 1 second epoch.

12. 0° = vertical, 90° = horizontal. 180° = inverted. Subject anterior inclination is a positive value, posterior is negative. Mediolateral inclination does not affect sign of posture value (i.e. sideways tilt).



### Data Output – Transmitted Data

Data output is in the form of a number of messages, each of which can be enabled or disabled.

Parameter	Reporting Frequency (Hz)	Range	Units	Description
<b>General Data Packet</b>				
Heart Rate	1	25 – 240	BPM	Beats per Minute
Breathing Rate	1	3 – 70	BPM	Breaths per Minute
Skin Temperature	1		°C	Invalid (-3276.8) always returned. Not supported.
Posture	1	±180	Degrees	
Activity Level	1	16	VMU (g)	Vertical = 0°, Inverted = 180°
Peak Acceleration	1	±16	g	
Battery Voltage	1	3.5 – 4.2	V	
Breathing Wave Amplitude	1	0 - 65534	bits	Indicative only
ECG Amplitude	1	0 – 0.05	V	Indicative only
ECG Noise	1		V	Indicative only
X Acceleration Min	1	±16	g	Vertical axis, output 1/10 g's
X Acceleration Peak	1	±16	g	
Y Acceleration Min	1	±16	g	Lateral axis
Y Acceleration Peak	1	±16	g	
Z Acceleration Min	1	±16	g	Sagittal axis
Z Acceleration Peak	1	±16	g	
ROG Status	1	R,O,G		See section 3.4.2
Strap Worn Status	1	0,1		0 = not worn.
Device Button pressed status	1	0,1		0 = not pressed
Battery Percentage of Full Charge	1	0 – 100	%	% of full capacity
<b>Breathing Data Packet</b>				
Breathing sensor output	18	0 – 4095	bits	Does not indicate breathing depth
<b>ECG Packet</b>				
ECG Sensor output	250	0 – 1023	bits	For debugging purposes only 1 bit = 0.013405 mV Reference generated at 60bpm
<b>Heart Rate R-R Packet</b>				
HR RR value	18	Minimum 250	ms	Alternating ± sign at new detection
<b>Accelerometer Data packet</b>				
X axis acceleration	50	±16		Scaled 0 – 4095, 2131 = 0g 83 = 1g (16g accelerometer)
Y axis acceleration	50	±16	bits	
Z axis acceleration	50	±16	bits	

1. All data packets are time stamped in milliseconds.

**BioHarness 3 Medical Data Sheet**

Parameter	Reporting Frequency (Hz)	Range	Units	Description	Invalid Value
<b>Summary Data Packet</b>					
Heart Rate	See 1. below	25 – 240	BPM	Beats per Minute	65535
Breathing Rate		3 – 70	BPM	Breaths per Minute	6553.5
Skin Temperature	2.		°C	Invalid always returned – not supported.	-3276.8
Posture		±180	Degrees	Vertical = 0°, Inverted = 180°	-32768
Activity Level		16	VMU (g)		655.35
Peak Acceleration		±16	g		655.35
Battery Voltage		3.5 – 4.2	V	3904 = 3.904V	65.535
Battery Level		0 – 100	%		255
Breathing Wave Amplitude		0-65534	LSB	Indicative only	65535
Breathing Wave Noise		N/A	V		65535
Breathing Rate Confidence		N/A	%		255
ECG Amplitude		0 – 0.05	V	Indicative only. 0.000001 resolution. 2376=0.002376V	0.065535
ECG Noise		0 – 0.05	V	Indicative only.. 0.000001 resolution. 1245 = 0.001245V	0.065535
Heart Rate Confidence		0 – 100	%		255
HR Variability		0 - 280	ms		65535
System Confidence		0 – 100	%	Physiological data validity	255
Galvanic Skin Response		N/A			
ROG Status		R,O,G		See section 3.4.2	0
Vertical Acceleration Min		±16	g	-83 = -0.83g	-327.68
Vertical Acceleration Peak		±16	g	1225 = 12.25g	-327.68
Lateral Acceleration Min		±16	g		-327.68
Lateral Acceleration Peak		±16	g		-327.68
Sagittal Acceleration Min		±16	g		-327.68
Sagittal Acceleration Peak		±16	g		-327.68
Device Internal Temperature		0 – 100	°C	612 = 61.2	-3276.8
Status Info				16 bit number. See 3. below	0
Link Quality		0 - 254		High number = high quality	255
RSSI		-127 – 127	dB	-5 = -5dB	-128

Page 6 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

**BioHarness 3 Medical Data Sheet**

Tx Power	-30 – 20	dBrn	10 = +10dBrn	-128
Estimated Subject Core Temperature	33 – 41	°C	386=38.6	6553.5
Aux ADC Channel 1	0 - 65534		Implementation specific	65535
Aux ADC Channel 2	0 - 65534		Implementation specific	65535
Aux ADC Channel 3	0 - 65534		Implementation specific	65535
Reserved				

1. The Summary data packet has a configurable reporting frequency, in the range 1 sec ~ 18 hrs. Data reported is the latest value for each parameter at time of transmission, other than Activity, Peak, Max & Min accelerations, which use the reporting interval as the epoch over which they are calculated.
2. Invalid Values may be reported if the data is not available at the time of transmission, or the device does not support that parameter. The BioHarness 3 Medical does not support Skin Temperature.
3. Status Info is a 16 bit number which flags the following parameters. Full descriptions and values can be found in the *Bluetooth Comms Link Specification*.

DWDL	Device Worn Detection Level
BPDF	Button Press Detection Flag
NFTG	Not Fitted To Garment
HRUF	Heart Rate Unreliable Flag
RRUF	Respiration Rate Unreliable Flag
STUF	Skin Temperature Unreliable Flag
POUF	Posture Unreliable Flag
ACUF	Activity Unreliable Flag
HRVUF	Heart Rate Variability Unreliable Flag
ECTUF	Estimated Core Temperature Unreliable Flag

Page 7 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

**Data Output – Logged Data****Logging Modes**

- |                          |                      |
|--------------------------|----------------------|
| ✓ General (default)      | ✓ Summary            |
| ✓ General + ECG          | ✓ Summary + Waveform |
| ✓ General + Acceleration |                      |

Where used, "Bits" refers to raw ADC output throughout. Note that some parameters are logged with greater resolution than is possible for transmitted data.

**General Log**

Parameter	Reporting Frequency (Hz)	Range	Units	Description
Heart Rate	1	25 – 240	BPM	
Breathing Rate	1	3 – 70	BPM	
Skin Temperature	1	N/A	°C	Not supported.
Posture	1	±180	Degrees	
Activity Level	1	16	VMU(g)	Vertical = 0° Inverted =180°
Peak Acceleration	1	±16	g	
Battery Voltage	1	3.5 – 4.2	V	
Breathing Wave Amp	1	0 – 65534	bits	Indicative
GSR Level	N/A	N/A	nS	Indicative
ECG Amplitude	1	0 – 0.05	V	Indicative
ECG Noise	1	0 – 0.05	V	Indicative
X Acceleration Min	1	±16	g	
X Acceleration Peak	1	±16	g	
Y Acceleration Min	1	±16	g	
Y Acceleration Peak	1	±16	g	
Z Acceleration Min	1	±16	g	
Z Acceleration Peak	1	±16	g	
Breathing Sensor output	18	0 - 4095	bits	
HR RR Value	18	250 – 1500	ms	Alternating ± sign on new detection

**ECG Log**

Parameter	Reporting Frequency (Hz)	Range	Units	Description
ECG	250	0 – 4095	Bits	Indicative

**Accelerometer Log**

Parameter	Reporting Frequency (Hz)	Range	Units	Description
Acceleration Magnitude	100	±160	g x 10	$\sqrt{X^2 + Y^2 + Z^2}$

***BioHarness 3 Medical Data Sheet*****Summary Log**

Parameter	Reporting Frequency (Hz)	Range	Units	Description
Heart Rate	1	25 – 240	BPM	
Breathing Rate	1	3 – 70	BPM	
Skin Temperature	1	N/A	°C	Invalid returned -3276.8
Posture	1	±180	Degrees	
Activity Level	1	16	VMU(g)	Vertical = 0°
Peak Acceleration	1	±16	g	
Battery Voltage	1	3.5 – 4.2	V	
Breathing Wave Amp	1	0 – 65534	bits	Indicative
Breathing Wave Noise	1	N/A		
Breathing Rate Confidence	1	N/A	%	
ECG Amplitude	1	0 – 0.05	V	Indicative
ECG Noise	1	0 – 0.05	V	Indicative
Heart Rate Confidence	1	0 – 100	%	
Heart Rate Variability	1	0 – 65534	ms	
System Confidence	1	0 – 100	%	
GSR	1	N/A	nS	nano Siemens
ROG	1	R, O, G		0 = invalid
Vertical Acceleration Min	1	±16	g	
Vertical Acceleration Peak	1	±16	g	
Lateral Acceleration Min	1	±16	g	
Lateral Acceleration Peak	1	±16	g	
Sagittal Acceleration Min	1	±16	g	
Sagittal Acceleration Peak	1	±16	g	
Internal Device Temperature	1	-40 – 80	°C	
Status Info	1			
Link Quality	1	0 – 254		0=Lowest quality
RSSI	1	-127 – 128	dB	Received Signal Strength Indication
Tx Power	1	-128 – 128	dBm	
Estimated Core Temperature	1	33 – 41	°C	Under Development
Auxiliary ADC Channel 1	1	0 – 4095	Bits	
Auxiliary ADC Channel 2	1	0 – 4095	Bits	
Auxiliary ADC Channel 3	1	0 – 4095	Bits	

Page 9 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

**BioHarness 3 Medical Data Sheet****Summary and Waveform Log**

Parameter	Reporting Frequency (Hz)	Range	Units	Description
All summary parameters	1			As Summary Log Format
Breathing Sensor Waveform	25	*		
Vertical Axis Accelerometer	100	0 – 4095	Bits	Centered on 2048 1g = 83
Lateral Axis Accelerometer	100	0 – 4095	Bits	Centered on 2048 1g = 83
Sagittal Axis Accelerometer	100	0 – 4095	Bits	Centered on 2048 1g = 83
ECG	250	0 – 4095	Bits	Indicative
Heart Rate RR intervals	Per R detection	250 – 1500	ms	40 – 240bpm equivalent
Breathing BB intervals	Per B detection	850 – 15000	ms	4 – 70Bpm equivalent
Event	Per event			See Event Descriptions

\*Raw breathing sensor output.

**Event Log**

Parameter	Reporting Frequency (Hz)	Description
Event	Per event	See event descriptions

**Event Descriptions**

Timestamp	Event Code	Type	Source	EventID	Event Data
YYYY/mm/dd/ms	See 1	System	Bluetooth	See 2	Event description e.g. 'Worn status changed from 100% to 0%'
			Button Press		
			Emergency Press		
			Battery Low		
			Diagnostics		
	See 1	Physiological	ROG Change		
			Worn Detection		
			HR Reliability Change		
			Fall Detection (see 3.)		
			Jump Detection		
			Dash Detection		

1. 16 bit Event Code= Event Type + Event Source + Event ID

2. 6 bit Event ID

3. Available on demand. Tested using young subjects on a crash mat.



### RF Characteristics

#### Bluetooth

Bluetooth Compliance	Version 2.1 + EDR
Supported Profile	Serial Port
Discoverability	Configurable
Frequency	2.4 to 2.835 GHz
Output Power	10 dBm
Operating Range	Up to 300ft / 100m
Sensitivity	Up to 300yds with long range receiver antenna (Dependent on Bluetooth receiver components)
Antenna Type	-91 dBm Internal

### Red / Orange / Green Subject Status Indication

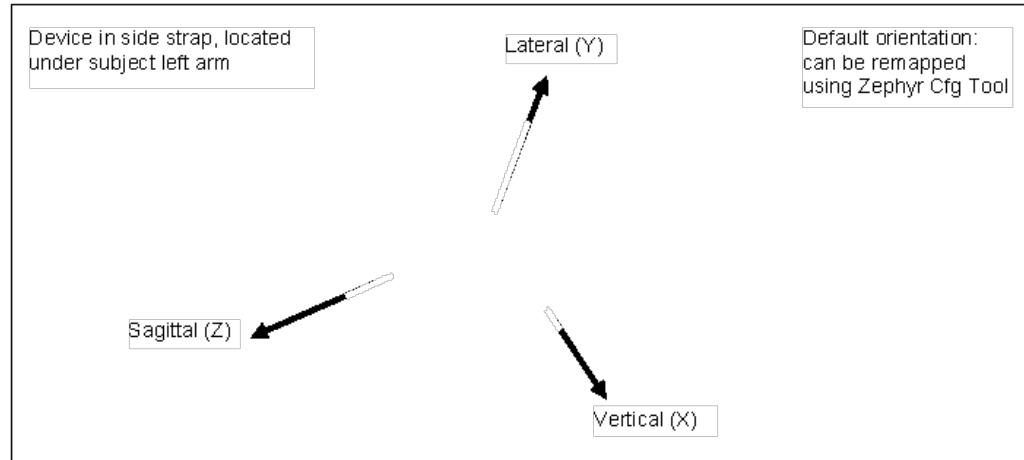
This is a value which is calculated in the device. It is dependent upon a number of thresholds for:

- ∨ Heart Rate
- ∨ Breathing Rate
- ∨ Activity level

Current and previous Heart Rate and Breathing Rate values are used in conjunction with activity level to establish a subject's status, using Zephyr proprietary algorithms.

Threshold levels are stored within the device and are configurable by USB.

### Accelerometer Axis Orientation

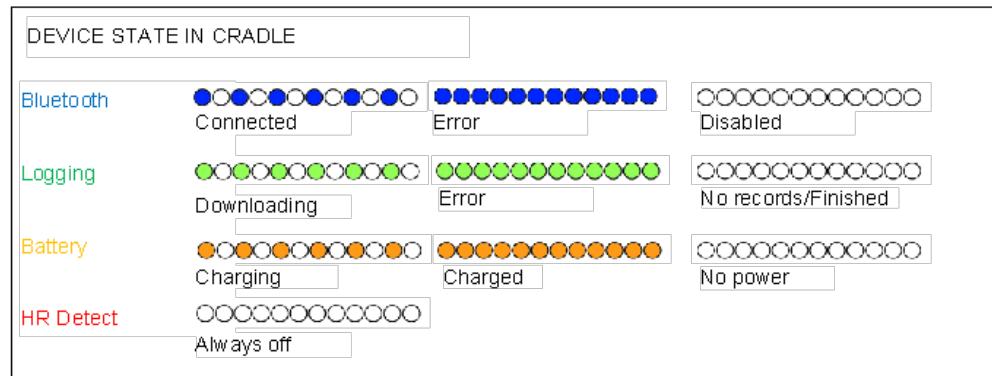
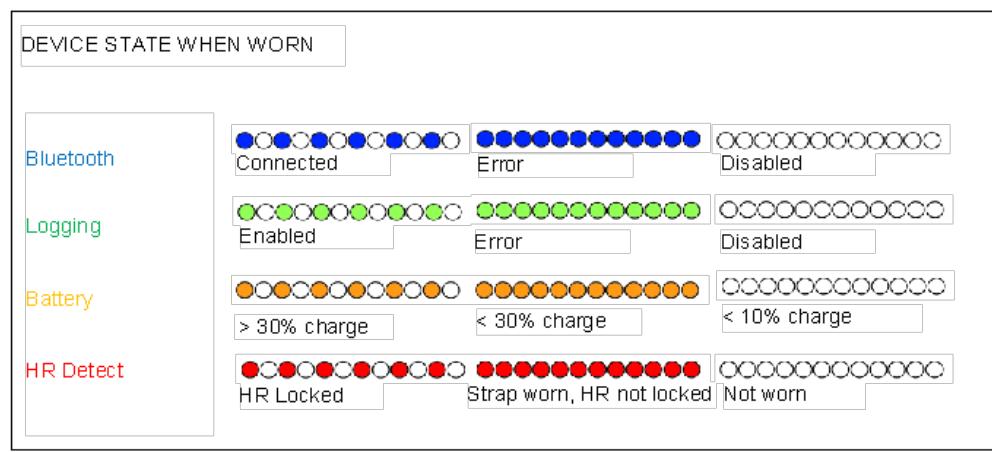


**LED Behaviour**

The BioHarness module can operate in four modes:

- ✓ Transmit data by Bluetooth
- ✓ Log data to internal memory (no transmit)
- ✓ Transmit and log the same data simultaneously
- ✓ Sample data, but not transmit or log until requested by BT

The device can be configured to these modes using the Zephyr Config Tool.



**Standards/Compliance/Certification**

The BioHarness has been designed to conform to the following:

EC38 Type:	Type 3
RTTE:	Directive 1999/5/EC
Contains Transmitter Module:	
FCC ID:	T7V1315

**Environmental**

Operating Temperature	-30°C / +60°C
Storage Temperature	-40°C / +85°C
Charging Temperature	0°C / +45°C
ESD	IEC 801-2KV
IP Rating:	IP55

**Portable Military Standards 810F Pending**

High Temperature:	501.4
Low Temperature:	502.4
Temperature Shock	503.4
Low Pressure:	500.4
Solar Radiation:	505.4
Rain & Blowing Rain:	506.4
Humidity:	507.4
Salt Fog:	509.4
Dust:	510.4
Vibration:	514.5
Shock:	516.5

**FCC Declaration**

NOTE: THE MANUFACTURER IS NOT RESPONSIBLE FOR ANY RADIO OR TV INTERFERENCE CAUSED BY UNAUTHORIZED MODIFICATIONS TO THIS EQUIPMENT. SUCH MODIFICATIONS COULD VOID THE USER'S AUTHORITY TO OPERATE THE EQUIPMENT.

This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) this device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

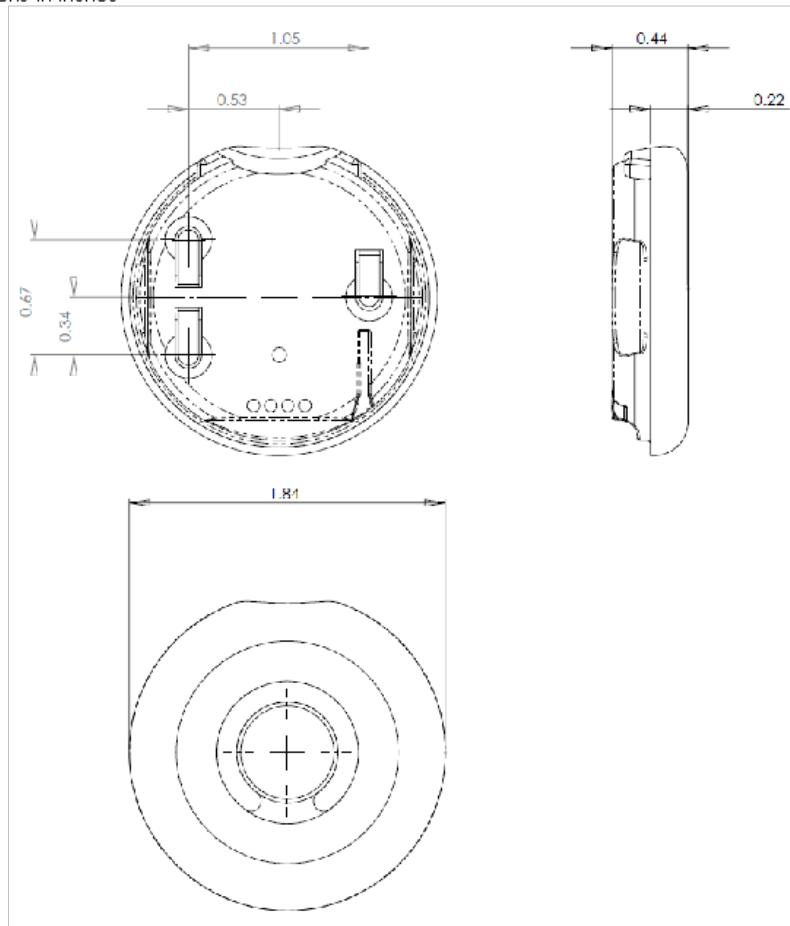
Any computer used in conjunction with this device must be covered by a Declaration of Conformity or must be FCC certified in its own right.

***BioHarness 3 Medical Data Sheet*****Mechanical Characteristics**

Dimensions	BioHarness module	28 (Diam) x 7 mm (1.84 x 0.44 inches)
	Charging Cradle (Single device)	80w x 24d x 37h mm (2.5 x 1.6 x 1.1 inches)
Weight	Strap (Large)	71 grams
	BioHarness module	18 grams
Case Material	PC	Polycarbonate

**BioHarness**

All dimensions in inches



Page 14 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

***BioHarness 3 Medical Data Sheet*****Accessories**

Part Numbers for the Zephyr BioHarness™ BT and associated components:

Component	ZPN
BioHarness™ 3 Module	9600.0254
BioHarness™ Smart Fabric Strap Side fitting XS to M adjustable	9600.0262
BioHarness™ Smart Fabric Strap Side Fitting M to XL adjustable	9600.0265
BioHarness™ Smart Fabric Strap Side Fitting L to XXL adjustable	Pending
BioHarness™ Single Unit Charging Cradle	9600.0257

**Cleaning & Sterilisation**

- ✗ TBD

**Hazards**

- ✗ Subjects fitted with a heart pacemaker should not use this device
- ✗ Device should not be worn in explosive atmospheres (such as gas stations)
- ✗ Device should not be worn near blasting areas where radio detonation methods may be used
- ✗ Charging at high temperatures has risk of fire or explosion (> 45 °C).
- ✗ Unit should not be disposed of in fire

**Notes**

- ✗ Should not be used for swimming or similar water-based activities
- ✗ No user-serviceable components
- ✗ Warranty void if opened

The information in this document is believed to be accurate in all respects at the time of publication but is subject to change without notice. Zephyr Technology assumes no responsibility for errors or omissions, and disclaims responsibility for any consequences resulting from the use of information included herein. Additionally, Zephyr Technology assumes no responsibility for the functioning of undescribed features or parameters. Zephyr Technology does not assume any liability arising out of the application or use of any product, and specifically disclaims any and all liability, including without limitation consequential or incidental damages.

Zephyr Technology products are not designed, intended or authorised for use in applications intended to support or sustain life, or for any application in which the failure of the Zephyr Technology product could create a situation where personal injury or death may occur. Should Buyer purchase or use Zephyr Technology products for any such unintended or unauthorised application, Buyer shall indemnify and hold Zephyr Technology harmless against all claims and damages.

Page 15 of 15

Ph: +1(443) 569-3603  
9700.0136

Fax: +1(443) 926-9402  
© Zephyr Technology 2012

Web: [www.zephyranywhere.com](http://www.zephyranywhere.com)  
2012-07-26

## 7 Appendix B – Datasheet of Shimmer GSR sensor

### Shimmer GSR+ Module



#### INTRODUCTION

Shimmer GSR+ provides connections and front-end amplifications for one channel of Galvanic Skin Response (GSR) data acquisition (Electrodermal Resistance Measurement - EDR). Compatible with the Shimmer3 platform, the GSR+ module also boasts an additional 3.5mm connector for 2 extra channels of analog or digital data capture.

#### PRODUCT OVERVIEW

The Shimmer GSR+ module addresses challenges of mobility and provides high quality, scientifically reliable data. The Shimmer GSR+ monitors skin conductance between 2 residual electrodes attached to 2 fingers on one hand.

The 3.5mm jack 3V connector allows users to connect and power an external/third party device, supporting an extra 2 channels of analog or digital data acquisition. The GSR+ module is compatible with the Shimmer3 platform and hardware. All development tools and enabling applications are compatible with the Shimmer3 platform.

#### KEY FEATURES

- 3.5mm jack connector for 2 extra channels of analog or digital data capture
- Dual channel GSR scientifically reliable data acquisition
- EEPROM storage device (on the GSR+ expansion board) enables expansion board detection and identification as well as 2032 bytes of data storage available to user
- Validated for use in biomedical-oriented research applications
- 4 digitally controlled measurement ranges which developers use to ensure accurate measurements across a variety of test subjects in real world deployments
- Open system with no proprietary connectors, extensible software and data format

#### APPLICATIONS

GSR+ Module is compatible with the Shimmer3 platform and can be applied to a variety of applications such as:

- Affective computing and cognitive factors
- Connected/ digital health solutions
- Stress detection and analysis
- Emotional engagement
- Psychological arousal (excitement, mental effort, shock etc.)
- Marketing research
- Weight and nutrition management

# Shimmer GSR+ Module



## TECHNICAL SPECIFICATIONS

<b>Current Consumption<sup>1</sup>:</b>	60µA
<b>Measurement Range<sup>2</sup>:</b>	10kΩ - 4.7MΩ (.2uS - 100uS) +/- 10%, 22kΩ - 680kΩ (1.5-45uS) +/- 3%
<b>Frequency Range<sup>3</sup>:</b>	DC-15.9Hz
<b>Connections:</b>	GSR Input 1 (Red), GSR Input 2 (Black); Hospital-Grade 1mm Touchproof IEC/EN 60601-1 DIN42-802 jacks Auxiliary Analog/Digital input: 3.5mm 4-position jack
<b>Bias voltage across GSR Input:</b>	0.5V
<b>Input Protection:</b>	RF/EMI filtering, Current limiting, GSR Inputs Include defibrillation protection (survive only not repeat <sup>1</sup> )
<b>Dimensions:</b>	65mm x 32mm x12mm

1. Calculated specification assuming that on-board EEFRCM is inactive and no external sensor is attached and powered via the analog/digital input channels; exact value is subject to environmental and component variation  
 2. % Error is tabulated average across the measurement range  
 3. Calculated specification, exact value subject to environmental and component variation

## SUPPORTING APPLICATIONS

Calibration: Shimmer 9DoF Calibration
Synchronisation of Data: Multi Shimmer Sync for Windows, Multi Shimmer Sync for Android, Multi Shimmer Sync for SD
ShimmerSensing LabVIEW Instrument Driver
Shimmer MATLAB Instrument Driver
Shimmer Java/Android API
ShimmerConnect: C# API/ .NET Development



## SHIMMER3 UNIT SPECIFICATIONS

<b>Processing:</b>	TI MSP 430 microcontroller (24MHz, 16Bit)
<b>Communication:</b>	Bluetooth – RN42
<b>Storage:</b>	Integrated 2GB microSD card slot
<b>Battery:</b>	450mAh rechargeable Li-ion
<b>Integrated Motion Sensing:</b>	<ul style="list-style-type: none"> <li>◦ WideRange Accel: +/-2g, +/-4g, +/-8g, +/-16g</li> <li>◦ LowNoise Accel: +/-2g</li> <li>◦ Digital Mag, Gyro, Pressure Sensor</li> </ul>

## SUPPORTING HARDWARE & ACCESSORIES

- Optical Pulse Sensing Probe
- Finger Electrodes
- Biophysical Leads
- Straps, Documents, Charger, Case

## Shimmer International Offices:

Europe – Dublin, Ireland.  
 USA – Boston, MA.  
 Asia – Kuala Lumpur, Malaysia.

Web: [www.ShimmerSensing.com](http://www.ShimmerSensing.com)  
 Email: [info@ShimmerSensing.com](mailto:info@ShimmerSensing.com)

© Copyright 2014 Shimmer  
 Specifications are subject to change without notice  
 S-S/GSR+-V2.1

## 8 Appendix C – Questionnaire definitions

This section includes the definitions of the Factors and of the Sub-factors of the EQ developed within the EXPERIENCE subproject. A short representative open question is also included, which is useful for the experimenter to provide the user with a simple idea of each Factor/Sub-Factor to be evaluated.

More information on bibliographical references about Factors and Sub-Factors' definitions will be reported in a paper in preparation.

### 8.1 Factor 1: USABILITY

It indicates how useful the exoskeleton is for you to carry out the task, if it suits you and whether it is pleasant to use it.

*Is it useful to me?*

- **Effectiveness:** It describes whether you, together with the exoskeleton, can achieve the established goals.

*Is this useful for me to achieve my goals?*

- **Efficiency:** It measures the possibility of reaching a goal by spending less resources as possible, that is measuring if it is possible for you to get the maximum output with minimum effort.

*Is it useful for me to achieve my goals in a cost-effective way?*

- **Satisfaction:** It measures how much you positively evaluate the characteristics of the exoskeleton and the services connected to the assistance.

*Does it satisfy me in all its parts and functions?*

### 8.2 Factor 2: ACCEPTABILITY

It evaluates how much you accept the exoskeleton and how much you would be willing to introduce it into your everyday life.

*Can I accept it without any doubts?*

- **Attitude towards technology:** It measures your attitude towards the exoskeleton and technology, what you think and how you react when you interact with technology.

*What is my attitude towards technology and the exoskeleton?*

- **Self-Efficacy:** It evaluates how much you think you have the ability to perform a task, if you believe you can achieve a goal using the exoskeleton.

*Do I feel able to deal with the exoskeleton and the task?*

- **Motivation:** It measures your willingness to use the exoskeleton and your dedication to the task.

*Am I motivated to use the exoskeleton?*

- **Comfort:** It detects the level of well-being you perceive while walking with the exoskeleton, both physically and psychologically.

*Do I feel comfortable when I use the exoskeleton?*

- **Safety:** It evaluates how safe you feel while using the exoskeleton.

*Do I feel safe when I walk with the exoskeleton?*

### 8.3 Factor 3: PERCEPTIBILITY

It measures the effects and the influences that the use of the exoskeleton has on your emotions, perceptions and quality of life.

*What do I perceive emotionally and sensorially?*

- **Embodiment and Ownership:** It refers to the perception of one's body, so it measures how much you feel the exoskeleton as a part of yourself.

*How does my perception of the body change when I walk with the exoskeleton?*

- **Agency:** It evaluates how much you feel you have control over your movements, while walking with the exoskeleton.

*Do I feel the control over my body (over my legs), and over my actions, when I walk with the exoskeleton?*

- **Emotion and Attachment:** It measures your emotions while using the exoskeleton, in terms of fear, anxiety, etc...; it indicates the "emotional bond" that is formed between you and the exoskeleton.

*How do I emotionally feel when I walk with the exoskeleton?*

- **Health and Quality of Life:** It describes what consequences the insertion of the exoskeleton could have on your life and well-being.

*Will I have benefits by using the exoskeleton?*

### 8.4 Factor 4: FUNCTIONALITY

It measures your perception of the characteristics of the exoskeleton in terms of ease of learning, flexibility of interaction, reliability and workload.

*Do the features of the exoskeleton facilitate me in the task I perform?*

- **Learnability:** It measures how easy or hard it is for you to learn to use the exoskeleton.

*Was it easy to learn how to use the exoskeleton?*

- **Flexibility:** It indicates how many tasks you can do and all the ways the exoskeleton can be used to perform the same task (for example which gait and start mode are provided).

*What can I do with the exoskeleton and in how many ways can the different functions be performed?*

- **Robustness and Reliability:** It measures your perception of robustness of the exoskeleton and the level of support provided by it.

*Is it capable of giving me support and working properly?*

- **Workload:** It measures the effort and commitment you believe you used in the task with the exoskeleton, both mentally and physically.

*Was it tiring to use the exoskeleton?*