Assessment of the psychophysiological state during walking with a treadmill-based exoskeleton

I. Pecoraro[1], N. L. Tagliamonte[1], C. Tamantini[1], F. Cordella[1], F. Bentivoglio[1], I. Pisotta[2], A. Bigioni[2], F. Tamburella[2], M. Lorusso[2], P. Argentieri[2], M. Molinari[2], L. Zollo[1]
[1]*Research Unit of Advanced Robotics and Human-Centred Technologies, Università Campus Bio-Medico di Roma, Rome*
[2]*Laboratory of Spinal Rehabilitation and Laboratory of Robotic Neurorehabilitation, Fondazione Santa Lucia, Rome*
*Corresponding author: `n.tagliamonte@unicampus.it`

***Abstract*—Rehabilitation robots are able to quantitatively assess biomechanical performance but they typically do not provide any information on the users' subjective experience during the execution of motor tasks. In the framework of gait rehabilitation aided by treadmill-based exoskeletons, we developed a method for the assessment of the users' psychophysiological state. By using a Fuzzy logic approach, four indicators can be estimated based on the recording of physiological signals. The method was tested on a group of four healthy participants walking with the Lokomat robotic gait trainer and the correlation among different pairs of indicators was evaluated.**

I. INTRODUCTION

Neurorehabilitation allows people with neurological diseases and gait disorders to recover independent walking in daily life. Conventional therapy might be enhanced by means of exoskeleton-aided training, with the possibility of collecting data on the subjects' motor performance based on sensors embedded in the robotic devices. Anyhow, rehabilitation robots typically do not provide information on the subjective experience of users. Many attempts have been made to develop reliable methodologies for the identification of the user's state from the analysis of facial expressions and posture [1]. Anyhow, the most effective solutions exploit physiological signals to determine user's PsychoPhysiological (PP) state, e.g. during the interaction with video games or robotic systems [2]. Due to the lack of studies investigating the PP state during the use of lower-limb assistive/rehabilitation exoskeletons, the objective of the present work was to develop a method for the PP assessment of exoskeleton-assisted treadmill walking and to preliminary test it with healthy participants. The presented protocol and methods were developed by the Authors within the framework of a research project aiming at providing developers of lower-limb exoskeletons and clinical experimenters with a tool capable of catching the subjective perspective of users, who are considered to be most important source of information for the evaluation and the benchmarking of robot-aided walking. Within this project the analysis of the user experience is also analyzed based on a novel purposely developed multi-factor questionnaire [3].

II. MATERIALS AND METHODS

A. Experimental protocol

Four healthy participants (1 male and 3 female, 34.0 $\pm$ 15.7 y.o.) took part in the study. Experimental tests were conducted with the treadmill-based exoskeleton Lokomat Pro (Hocoma), available at Neurorehabilitation 1 Department of Fondazione Santa Lucia (FSL). Each participant performed at least 2 preliminary walking sessions with the Lokomat to become familiar with it. After the familiarisation sessions, a measurement session was carried out for data collection. Each (familiarisation or measurement) session lasted about 60 min including preparation time. Measurement sessions were split in two phases: *i)* participants were seated in a comfortable position for 4 min, with their eyes closed and acoustically isolated to promote relaxation (*Resting Baseline*, RB); *ii)* participants walked in interaction with the exoskeleton for 20 min, with the assistance level set similarly to the familiarization session (*Exoskeleton Training*, ET). The protocol was approved by the FSL Ethics Committee (prot. no. CE/PROG 746).

B. Physiological sensors

Physiological signals were measured by means of two commercial devices: the Zephyr BioModule 3 (Medtronic), a chest belt measuring the Respiration Rate (RR) and electrocardiogram (ECG), and the Shimmer GSR+ (Shimmer), acquiring the Galvanic Skin Response (GSR) by means of electrodes on the index and middle finger. Sensor data, synchronized by a C# interface, was sent to a host PC via the Bluetooth Low Energy protocol (the ECG signal was sampled at 250 Hz while the other signals were sampled at 25 Hz).

C. Data analysis

Three features were extracted from the ECG data: the Heart Rate (RR) and two Heart Rate Variability (HRV) metrics, i.e. the RMS of successive heart beats (rMSSD) and the power distribution in the Low-Frequency (LF) band (0.04$-$0.15 Hz). 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 new method, based on Fuzzy logic, has been developed for the extraction of four PP indicators of interest: *stress level* (measure of perceived safety), *fatigue level* (measure of prolonged physical engagement), *energy expenditure* (measure of comfort), *attention level* (measure of involvement). The physiological signals (input of the Fuzzy

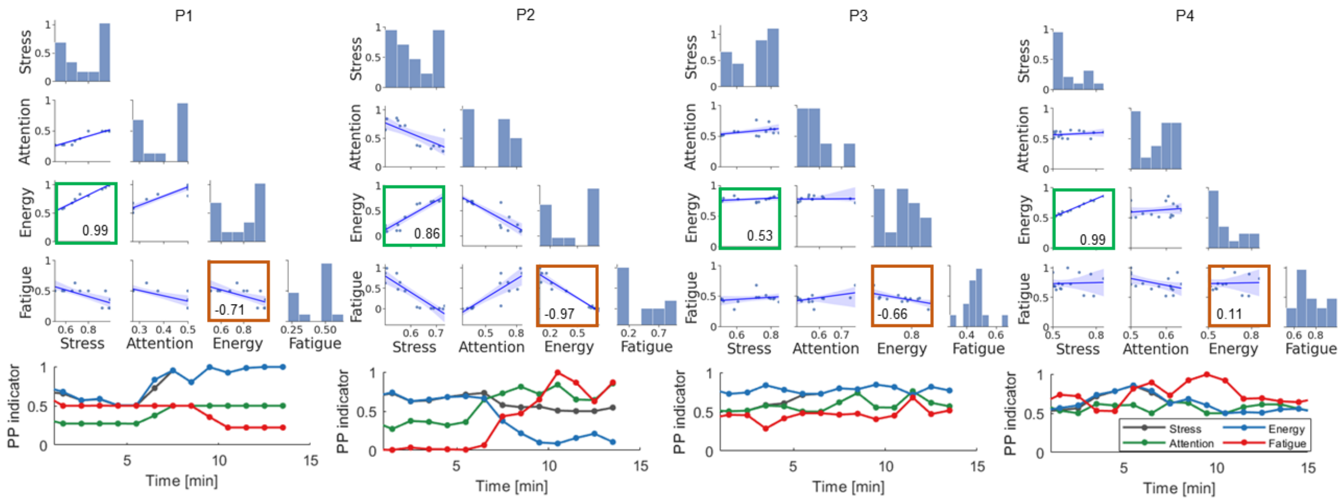

Fig. 1. First row: Pairwise correlations of the PP indicators (diagonal: univariate distribution of the data; other cells: linear regression models fitted on the scatter plots); positive stress-energy correlation (green boxes) and negative energy-fatigue correlation (red boxes) were found (Spearman's correlation coefficients are labeled). Second row: Time-series of the PP indicators along 15 min of the ET recording.

model) of the ET phase were considered only for the last 15-min recording and were normalized with respect to the data collected during the RB phase. For each physiological signal, the membership functions were created by taking into account the histogram distribution and by considering *low*, *medium* and *high* levels [4]. IF/THEN rules were defined based on trends of variation of physiological signals retrieved from a careful analysis of the scientific literature [5], [6], [7]. These rules combine all the input physiological data to estimate the four PP indicators in time intervals of 1 min, considered to be suitable for reasonable changes within the present application. To find correlations among PP indicators a participant-specific and a global statistical analysis were performed. In particular, the Spearman's correlation coefficient ρ was calculated in pairwise comparisons.

III. RESULTS AND DISCUSSION

In Fig. 1 the pairwise correlations (first row) and the time-series of the four PP indicators along 15 min of recordings (second row) are reported. For the four participants, we found a high correlation ($|\rho| \geq 0.5$) in two cases: positive correlation between stress level and energy expenditure and negative correlation between energy expenditure and fatigue level. Hence, as energy expenditure increases, stress level increases and fatigue decreases. Other correlations for pairs of PP indicators were heterogeneous among participants. Negative correlation between fatigue and stress levels was common for P1 and P2 ($\rho = -0.72$ and $\rho = -0.84$, respectively). Different results were found for the attention-stress ($\rho = 0.91$ and $\rho = -0.66$ for P1 and P2, respectively), the energy-attention ($\rho = 0.89$ and $\rho = -0.85$ for P1 and P2, respectively) and the fatigue-attention ($\rho = -0.62$ and $\rho = 0.89$ for P1 and P2, respectively) correlations. A common trend for all participants was not clearly evidenced in PP time-varying patterns (Fig. 1).

IV. CONCLUSIONS

The aim of this work was the development of a method for the PP assessment of users whose treadmill walking is assisted by a lower limb exoskeleton. Due to the limited number of participants the method was demonstrated to be effective only in highlighting a correlation between energy expenditure and both stress and fatigue levels. Additional correlations in pairwise comparisons were heterogeneous and also no trends of variation in the time-series of the PP indicators were evidenced. In our ongoing work we are enlarging the group of participants, recruiting subjects with lesions of the central nervous system and extending the method to the use of an overground exoskeleton. Moreover, a correlation among PP indicators and subjective evaluations, assessed by means of a dedicated questionnaire, is going to be performed. The results of our work are expected to provide an international facility developed for the assessment of bipedal locomotion (EUROBENCH European project, H2020-779963) with a tool suitable for the benchmarking of lower-limb exoskeletons.

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