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MINDWALKER: Going One Step Further with Assistive Lower Limbs Exoskeleton for SCI Condition Subjects

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Abstract— **This paper presents MINDWALKER, which is an ambitious EC funded research project coordinated by Space Applications Services aiming at the development of novel Brain Neural Computer Interfaces (BNCI) and robotics technologies, with the goal of obtaining a crutch-less assistive lower limbs exoskeleton, with non-invasive brain control approach as main strategy. Complementary BNCI control approaches such as arms electromyograms (EMG) are also researched. In the last phase of the project, the developed system should undergo a clinical evaluation with Spinal Cord Injured (SCI) subjects at the Fondazione Santa Lucia, Italy.**

I. Introduction

MINDWALKWER [1] is funded by EC under an ICT research programme named e-Inclusion, that aims at improving inclusion in social life of European individuals, in particular those with reduced mobility (due to e.g. disability).

The research question that initiated this project can be stated following this way: could a lower limbs assistive exoskeleton system allow SCI subjects to recover mobility, relying on convenient, non-invasive BNCI control signals acquisition – EEG based as far as possible, and without the need for stability improvement accessories such as crutches (that cannot be used by quadriplegic subjects, and that prevent paraplegic subjects from using their arms and hands for daily life activities).

For that purpose MINDWALKER tackles challenging research directions in multiple areas (as illustrated on Fig. 1), in particular: assistive and rehabilitation robotics for walk empowering, and BNCI approaches for the control of robotic platforms aiming at empowering disabled subjects with walking ability. Additionally, MINDWALKER addresses how and how effectively can Virtual Reality (VR) based technologies support the training of patients so that they can prepare, in a safe and fully controlled environment, for the usage of assistive robotics technologies in their daily life.

This paper provides a review of the project's intermediary outcomes after two years, and also highlights the challenges and difficulties faced so far.

II. Target Applications Areas and End Users Survey

Although a number of medical conditions may lead to walking disability, the project primarily scoped spinal cord injuries originating disabilities. Such conditions are usually irreversible and often result from a violent trauma which induces lesions at one or several locations in the spinal cord. Depending on the location and the magnitude of the lesions, effects may range from sensory discomfort in the toes, to full quadriplegia and breathing assistance requirement. Spinal cord condition may be complete (when the injury resulted in fully interrupted nervous connections) or incomplete.

For subjects with SCI originating disability, it is very relevant to consider EEG based technologies to control a robotic lower limbs assistive device, for two reasons:

1. SCI subjects often do not suffer from a brain trauma, therefore their brain capabilities are intact
2. As the spinal cord is injured, the approach therefore basically aims at wiring, with non-invasive techniques, the brain control signals to the assistive robotic exoskeleton – therefore short-cutting the injured, natural control path.

As part of the project, it is interesting to mention that a survey of SCI patients and relevant medical staff (therapists, medical doctors) has been carried out in the early phase of the work, to collect user requirements for MIDNWALKER. A total of 42 SCI patients and 14 medical staff attended the survey, and the resulting outcomes along with elicited requirements have been reported in a project deliverable in 2010 (publicly available online as a MINDWALKER deliverable: [2]).

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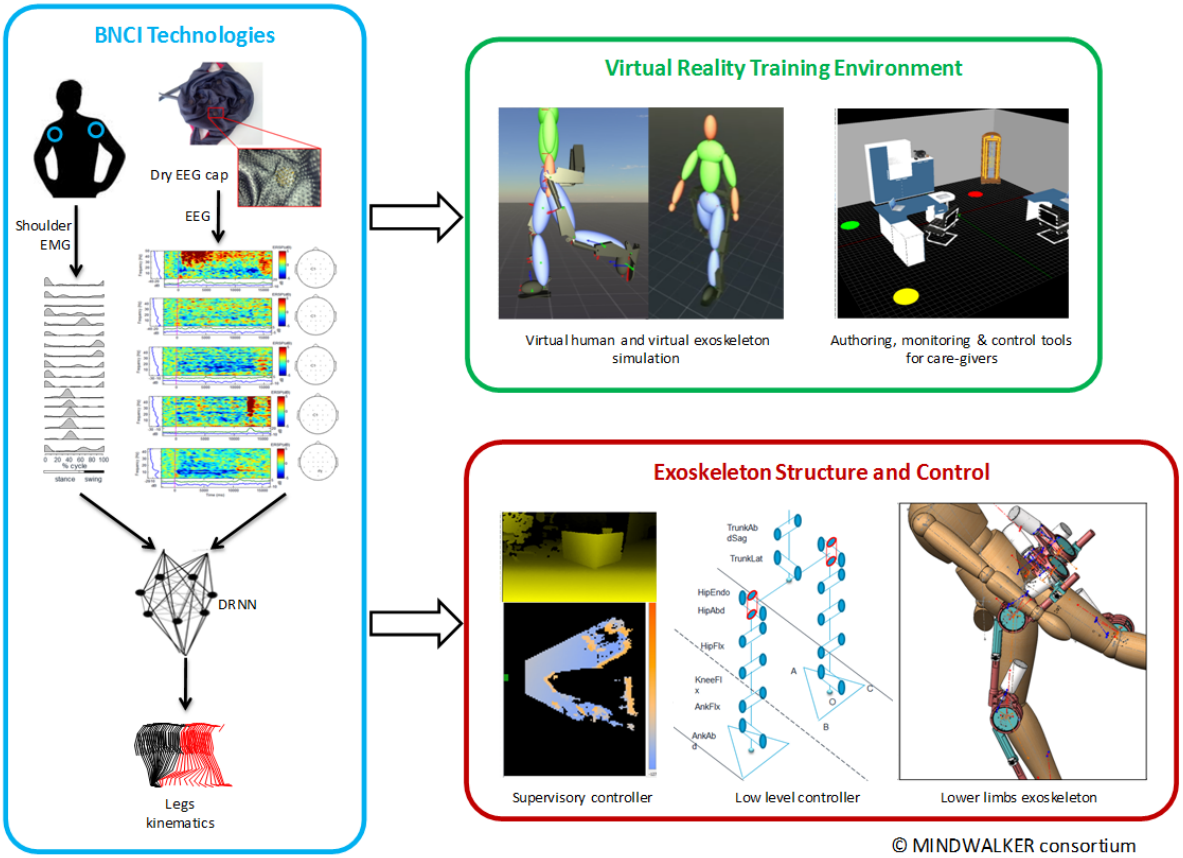

Fig. 1: MINDWALKER 3 main research areas

III. State of the Art and State of Play

A. Relevant Robotics Technologies

1) Walk assistance robotic systems

Progress with walk assistance robotic systems has recently been widely advertised, the latest system being EKSO [3][4] (formerly known as eLEGS) from the US company EKSO-bionics. In the last few years, several other walking assistance exoskeletons have caught the attention of the media, including: the ReWalk [5] system (one of the first ones) from the Israel company Argo, HAL [7] from the Japanese company Cyberdyne, and REX [6] from the New-Zealand company Rex-bionics. All these systems but REX require the patient to use crutches in order to preserve the stability. REX approach is instead to ensure the stability with very low speed and quasi static properties, along with an exoskeleton whose overall mass (which is greater than competitors' solutions) contributes to stability.

MINDWALKER takes a novel and challenging path compared to the competition, with the objective of developing a crutch-less lower limbs exoskeleton solution that can dynamically ensure the balance of the system consisting of the exoskeleton and the subject wearing it.

2) Control strategy

Popular control approaches are roughly categorized into two groups: (i) position control and (ii) impedance control.

In the position control, the trajectory of a gait cycle is controlled by measuring the angular positions of the joint. The advantage of this approach is that the gait cycle is accurately followed by the wearer. This is because, in a feedback control loop, the controller tries to minimize the deviation between reference position and actual position at the joints of the exoskeleton. This control method is implemented in the first Generation of the Lokomat [9] and the Joint-Coupled Orthosis for FES-Aided Gait [10]. However, with position control, different walking modalities require different related reference trajectories. And these reference trajectories are highly dependent on the walking velocities. Therefore, only walking modalities at discrete velocities are realizable.

Impedance control is described by a mass-damper-spring relationship between a position x and generalized force f as per the equation below:

$$f = m\ddot{x} + b\dot{x} + kx$$

where m is: the mass when x represents linear position, or the inertia when x stands for an angular position, b is the damping coefficient and k is the stiffness. Then, either: a) the mass-damper-spring system really exists; or b) it is a virtual system. The output of the system could either be a desired position or a desired force or torque, but the input is always the force or the torque applied at the joints of the exoskeleton. In impedance control, a gait pattern or trajectory is usually predefined which is similar in position control. However, the difference from position control is that the wearer can actually influence his walking pattern and the exoskeleton can adjust the amount of support based on the wearer's intention. Velocity and acceleration of the joint can be controlled much easier than in a position control. This control method is widely implemented in existing exoskeletons such as i.e. LOPES [11], IHMC-MAE [12] and BLEEX [13]. Moreover recent research shows that gait patterns or trajectories are not necessarily predefined when integrating neural network methods such as Central Pattern Generator (CPG) [37] with impedance control, which introduces more flexibility and robustness to the strategy of impedance control.

B. BNCI Technologies

1) Brain signal based approaches

Event Related Potentials (e.g. P300) and Steady State Visual Evoked Potentials (SSVEP) are two popular EEG based BNCI approaches often considered as having interesting potential for concrete applications. SSVEP are a resonance phenomenon arising mainly in the visual cortex when a person is focusing visual attention on a light source flickering with a given frequency. This cortical activity has furthermore a very good signal to noise ratio and is thus very relevant in the frame of BCI experiments. The other advantage of this method is that it does not require intensive training like other BCI methods but is rather based on potential detections. However as ERP and SSVEP both rely on stimulations of the subject (visual stimulation being a common approach), they may not always properly fit the constraints of specific or demanding applications.

As a more challenging, but more promising path to everyday applications, continuous translation of brain signals to control signal is an appealing approach.

Invasive BNCI to kinematics has been successfully demonstrated in 2005 with a quadriplegic patient for the control of an artificial hand, and also with rhesus monkeys experiments [8] [19] [14]. MINDWALKER considers such continuous conversion of brain signal to kinematic signal, however with non-invasive brain signal acquisition (EEG based). This actually makes the problem even more challenging, due to the difficulty of properly collecting and exploiting EEG signals.

2) EMG based approaches

EMG is considered a valuable bio-signal source for BNCI applications. Several existing upper limbs or lower limbs rehabilitation exoskeletons have been experimented with EMG perception in the limbs. EMG data is used either to trigger assistance in anticipation to the muscle activation (i.e. somehow intercepting electrical muscle activation signal), or to adjust support in proportion to EMG measurement characteristics (amplitude, location, etc.). [7]

C. VR and Training Environments for Rehabilitation

A number of studies and experiments have shown that Virtual Reality (VR) can be a valuable tool in support to rehabilitation training for disabled people [20][21]. For instance with LOKOMAT [15], VR is essentially used as a mean to stimulate, encourage and motivate the patients.

Highly immersive VR environments not only improve user motivation and training experience, but also increase BCI performances [16]. Mirelman for instance [17] finds a significantly larger increase of ankle power generation after training with virtual reality. According to [18], it is however unclear which characteristics of VR are most important, and whether (and how) most recent interaction technologies (e.g. with real time body and arms tracking) have potential to improve the effectiveness of VR support to rehabilitation.

IV. LOWER LIMBS EXOSKELETON

A. Mechanical Structure, Sensors and Actuators

An overview of the designed exoskeleton and knee joint CADs are provided in Fig. 2. The white cylinders are linear actuators (BLDC motor and ballscrew), chosen for their outstanding torque/weight ratio.

The actuation system of the exoskeleton is designed for efficiency. From drive electronics to motor, and from transmission to bearings, we have chosen the most efficient components we could find.

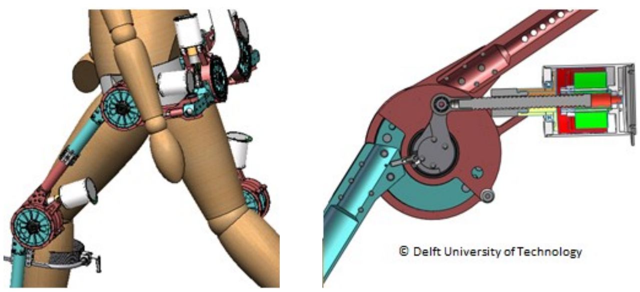

Fig. 2: Left: CAD of the exoskeleton structure and actuators. Right: close up on the knee joint and actuator

The actuation design is optimized to minimize the energy consumption for walking, while allowing enough torque to execute fast balance recovery motion. The optimization makes use of a quasi-static power-based model. Regenerative braking of the motor (used as a generator) is allowed in the model. The overall structure, hip and knee joints and actuators are currently being manufactured.

Fig. 3: PROPRIO FOOT prosthetic (OSSUR) used for the exoskeleton's ankles and feet

The ankles and feet come separately as contribution from OSSUR. Their existing PROPRIO FOOT prosthetic is considered a candidate for this purpose (with needed adaptations), though feasibility of this approach should further be confirmed [22] (Fig. 3). All included (except power pack), the exoskeleton weight is estimated to reach about 24 kg.

B. *Low Level and Supervisory Level Control*

1) *Approach to low level control*

A new method for controlling wearable exoskeletons is worked out in the project. Instead of using predefined joint trajectories, the control approach only relies on basic gait descriptors such as step length, swing duration, and walking speed. Gait analysis has been performed in order to design proper gait models, and to find out the impact of perturbations on the gait patterns.

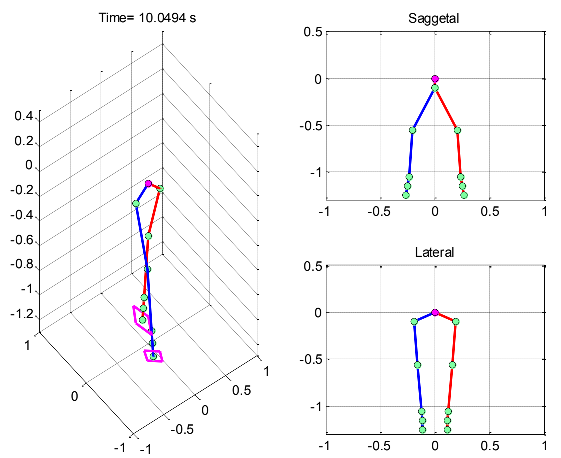

Fig. 4: 3D exoskeleton model used in the Model Predictive Controller (Matlab)

End point Model Predictive Control (MPC) is used with a 3D model of the exoskeleton (Fig. 4) to generate the online joint trajectories based on the gait parameters. Real-time ability and control performance of the method during the gait cycle has been studied, initially for the swing phase, and then over the overall cycle. Experiments have been performed by helping a human subject swing his leg with different patterns in the LOPES [23] gait trainer previously developed by Universiteit Twente. Results show [24] that the method is able to assist subjects to make steps with different step lengths and step durations without predefined joint trajectories and is fast enough for real-time implementation.

The designed MPC is able to predict correct mitigation behaviors (and the controller can accordingly generate suitable control torques) that should allow, in case of perturbation, to prevent irrecoverable loss of balance. Latest efforts address performances enhancement, so that the approach can safely handle in near real time a variety of situations.

2) *High level, supervisory Controller*

The Supervisory Controller forms a critical safety module in the MINDWALKER system, acting as the first point of inhibition for potentially dangerous actions. In its prototype form, the primary function of the Supervisory Controller (EXOC-SUP) is analogous to obstacle detection in robotic systems. It uses a Microsoft Kinect [25] to build a height map (digital elevation map) of the region ahead of the user, and detect obstacles in the region. The detected obstacles are then passed to the motion planner, which in turn includes the obstacles in the planning process, and inhibits the motion of the exoskeleton if needed.

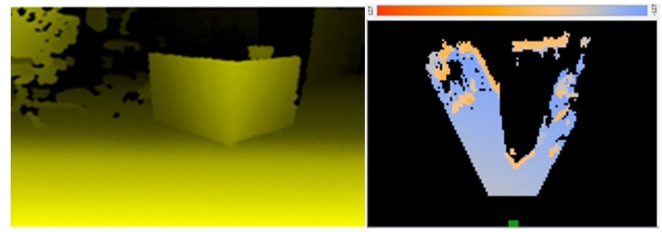

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Fig. 5: Depth map (left) and elevation map (right) generated at 15-30Hz for obstacles detection and notification to the motion planner

The Microsoft Kinect, along with an XSens MTi inertial measurement unit (IMU) [26], is mounted at the front of the exoskeleton, near the pelvis. It provides a dense 3D point cloud of the environment in front of the exoskeleton, including the floor directly ahead (Fig. 5). Additional work to extract regular shapes (such as cylinders, cuboids, spheres) from clusters of obstacle cells is foreseen.

V. BNCI Devices and Control Strategy

A. *EEG based control*

1) *Main research direction*

A challenging path to EEG based BNCI that has been a major motivation to setting up the project, is the concept of "ideation" - which is the EEG based counterpart of the invasive brain signal to kinematics approaches introduced previously in the state of the art. The expectation with this approach is that, ultimately, motor cortex EEG signal can be exploited for generating online legs kinematics angles corresponding to the walking pattern and pace as imagined by a subject. The feasibility of such an approach could not be confirmed at that stage, although experimental protocols carried out so far do not close the door to that approach.

The heart of the BNCI processing chain consists of a Dynamic Recurrent Neural Network (DRNN) [27][28] embedded as an OpenVIBE [30] module in which the BNCI chain is implemented. Visual stimulation of subjects with walking avatars rendered in virtual reality environments is additionally used in support to this part of the research.

The main challenge with the recording of EEG is artefacts: mechanical artefacts, due to relative movement of EEG cap electrodes during walk, produce random noise which is difficult to filter; and physiological artefacts, due to muscles activity in the vicinity of the cap. Independent components analysis (ICA) methods allow, in a certain extent, to identify the location of the signals and filter the ones that are known not to be relevant.

2) *More usual approaches consideration*

Besides "ideation" paradigm, more classical approaches are studied and developed for the needs of MINDWALKER

SSVEP in particular are considered a possibly relevant approach (illustrated in Fig. 6). It requires however that the subject has in his/her field of view the flickering images, so that the user may observe them, which may possibly be addressed in the project with the use of a lightweight, single eye see-through head-mounted display (under evaluation).

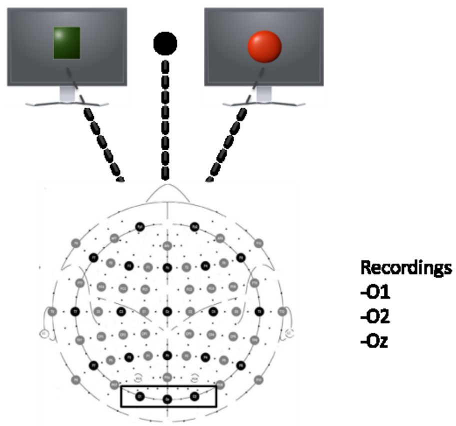

Fig. 6: Preliminary protocol using SSVEP in recordings in the occipital cortex. In the left screen the green button flickers at 5Hz, on the right screen the red button flickers at 10Hz.

B. EMG complementary approach

The electromyographic (EMG) activity of trunk and leg muscles during human adult locomotion is explained by few basic patterns (Fig. 7) independent of locomotion mode, direction, speed, and body support [31][32]. These patterns may be regarded as locomotor primitives. Due to the natural arm-leg coordination in human walking, leg motor control patterns can be reflected in the EMGs of arm muscles. Therefore arm EMGs could be used as an additional (or hybrid) control for the MINDWALKER exoskeleton.

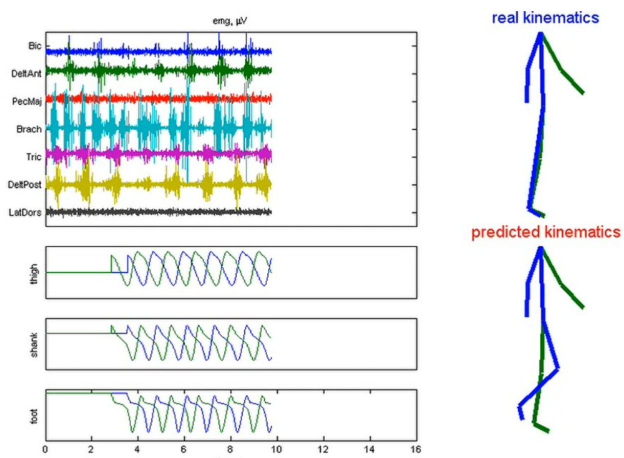

Fig. 7: Prediction of leg kinematics from arm-EMG signals. The subject was swinging his arms during upright standing (upper panel) while the produced arm EMGs were used to predict the locomotor rhythm of leg movements.

Looking for the rules of arm-leg coordination in human locomotion, various locomotor-related tasks and arm-leg coordination strategies for human locomotion have been studied in the project. Overall, these experiments provided new data on the reorganization and adaptation of the output of central pattern generators involved in the control of human locomotion and revealed the groups of arm and trunk muscles involved in most locomotor tasks in humans. Taking into account the above considerations and natural arm-leg coordination strategies, software in Matlab and Labview has been developed to process the multi-muscle EMG data to predict locomotor rhythm and leg movement kinematics based on natural arm muscle synergies (Fig. 7). This match is called “spinal map”.

We also recently demonstrated [29] that a DRNN is able to reproduce the elevation angles of the thigh, shank, and foot by means of only two EMG signals of the arm (rectified, filtered, and smoothed) recorded from the anterior and posterior deltoid muscles and used as DRNN input. At present we are able to use these EMG signals in real time (Fig. 8) for producing the 3 elevation angles of the lower limb segments. This can be accomplished when the subjects are in seated position.

Fig. 8: Left side, LOPES exoskeleton leg control (hip and knee angles) through online shoulder EMG processing (right side) of a subject performing arm swing.

Combined with other BCI procedures, this new task-dynamics recognition of the DRNN has implications for the development of diagnostic tools and prosthetic controllers. Hip and knee angles have been rendered online with the LOPES setup, demonstrating that shoulder EMG during arms swing can be exploited to control the walking pace of a lower limbs robotic exoskeleton.

C. Dry EEG cap

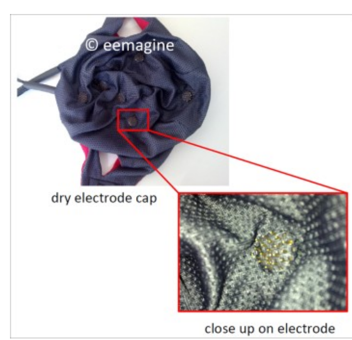

Fig. 9: Dry EEG cap prototype with fabric-embedded electrodes, developed by eemagine GmbH

Considering the important research axis dealing with EEG signal exploitation for the control of the lower limbs exoskeleton, an interesting additional perspective of the project was the development of a concept of dry EEG cap (Fig. 9) that could allow, contrary to more traditional wet caps, to be convenient for daily use (i.e. put-on / take-off in a few seconds, and easily cleaned and maintained). Multiple challenges are associated with the development of such a dry cap, ranging from the choice of materials for electrodes, to the ergonomics and strategy to distribute electrodes pressure equally on the head skin, and last but not least adequate signal amplification and noise filtering.

VI. Virtual Reality Training Environment

A. Motivation

The VRTE mainly aims at exploiting the use of Virtual Reality for providing an immersive framework to train users to reach a good level of confidence in the control of the exoskeleton before realizing the transition to the real exoskeleton.

The aim of the VRTE is threefold. It first supports the training of the DRNN (with a healthy user or with a SCI user) by visually stimulating the patient. Then, it supports the training of the user to control the exoskeleton through the use of virtual reality to gain experience in various situations. A simulation subsystem simulates a dynamic model of the exoskeleton coupled with a model of the subject's body to reproduce the same behavior as if the subject was controlling the real exoskeleton. Finally, it provides the medical personnel with the means to monitor and control the training phases and the performances of the user in the different stages of the virtual training process.

B. Approach

The VRTE setup and hardware configuration is depicted in Fig. 10. In this configuration, the patient is positioned in an actuated seat in front of a large 3D TV screen.

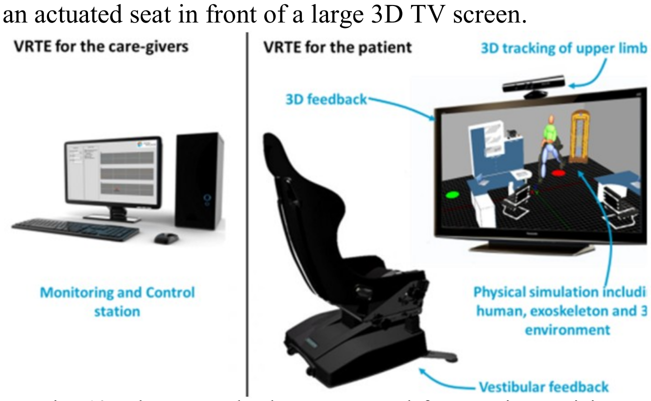

Fig. 10: The VRTE hardware setup – left: care-gives training authoring and monitoring. Right: patient training environment.

His/her upper body is tracked by a Kinect camera and the simulation displays a 3D virtual human representation. The upper body of this virtual human representation is controlled via the tracking data, and its legs are actuated by the Virtual Exoskeleton's controller, using BCI inputs. Vestibular feedback is provided to the patient by an actuated seat [33], which is controlled by the simulation using the simulated exoskeleton belt orientations (pitch and roll) as inputs.

The care-giver is located at the monitoring and control station, from where he/she can control the execution of the training session. Off-line, the virtual environment and the training scenario can be designed with the authoring tool.

C. VRTE main components

1) Physical simulation

In order for the user to experience and feel the balance and dynamics of the real system, and how he/she can influence it, realistic dynamic simulation of the system is required. The physics simulation relies on eXtended Dynamics Engine (XDE) [34] to simulate the virtual exoskeleton (4 active hinge joints and 3 passive sliders for each leg), the virtual human (16 links associated to 37 DOF), the virtual environment and their interactions.

The models of the simulated elements are defined in XML. The virtual exoskeleton and the virtual human models are robot-like model, from the dynamic simulation point of view. Both models have their own integrated controller. The model of the coupling between the exoskeleton and the human is constituted by a set of links between the two robots models. The simulation is interfaced to the same controller as the one of the exoskeleton (see section IV.B.1), in order to provide as realistic behavior and feedback as possible to the user.

2) Authoring tool

The authoring tool (Fig. 11) allows the medical staff to create scenarios for the user to follow during the training sessions.

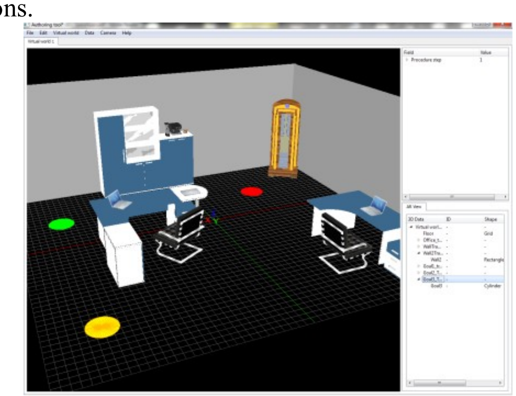

Fig. 11: Screenshot of the VRTE authoring tool

3D objects can be defined or imported from various standard formats. A procedure consists of different steps (waypoints) that can be edited by medical staff for training scenario definition. Each step may relate to one or more objects of the 3D scene. The authoring tool scene management relies on the OpenSceneGraph [35] toolkit.

3) Human body tracking

The human upper body tracking is performed (Fig. 12) using a Kinect camera, relying on OpenNI [36] and using XDE. The kinematic exoskeleton, output of the Kinect tracking system, is linked to the virtual human through several 6 DOF Cartesian couplings (one for each segment, characterized by a translation stiffness and damping).

The components of the VRTE are integrated together using a CORBA based communication bus called DSimi, which is a core XDE framework component, and that optimizes exchanges of data through standardized interfaces.

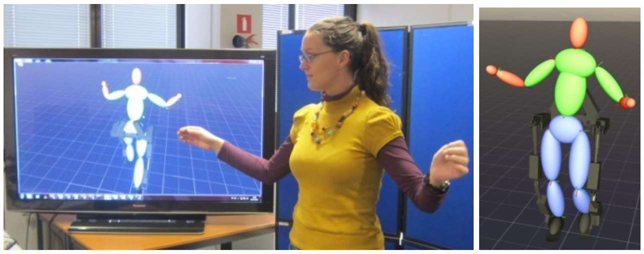

Fig. 12: Left: patient's upper-body tracking. Right: close up on the virtual human and exoskeleton rendering (preliminary concept).

VII. STATUS, CHALLENGES AND FUTURE WORK

MINDWALKER gathers a wide spectrum of expertise, addressing very different challenging research areas while promoting the vision of a concept of assistive lower limbs exoskeleton going one step further than existing walk assistance or rehabilitation systems so far.

Progress and experiments outcomes in the second year of the project led to refine suitable concepts and approaches for the development of a MINDWALKER prototype, and to realize the extent of subsequent challenges. Due to the nature of the project, integration in particular is obviously a major concern.

A major milestone will be the upcoming evaluation of the integrated solution with end users during the clinical evaluation phase, later this year. In the meantime, two more integration steps are foreseen, where partners will jointly experiment latest, consolidated versions of the subsystems.

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