SOLEUS

Title : SOLEUS Executive Summary Report

Abstract : This document is the Executive Summary Report of the SOLEUS ESA activity, aiming at concisely summarizing the motivations, developments and findings of the project. It is addressed to all audience interested in this study, including non-experts in this field of work.

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List of Abbreviations

ABT	AnyBody Technology
DC	Direct Current
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DoF	Degree of Freedom
ESA	European Space Agency
HMD	Head Mounted Display
MTU	Muscle Tendon Unit
MVC	Maximum Voluntary Contraction
SA	Space Applications Services
VR	Virtual Reality

1 Introduction

1.1 Motivation

During spaceflight, the human body is subject to physiological adaptation to the microgravity environment. Although some effects, like vestibular disorders, lead to temporary discomfort during some days, other reactions such as bone mineral loss or muscle atrophy affect the physical condition of astronauts in proportion to the time spent in space. These are major concerns for long-duration missions such as those on-board the ISS (several months) and for future planetary exploration missions to the Moon and Mars (several years).

Increasing time exposure of astronauts to microgravity for new missions requires a more thorough understanding of the issues met by astronauts in these conditions. Current countermeasures are not effective enough, as they only partially mitigate deconditioning effects. The development of new or significantly enhanced countermeasures is of paramount importance. The ESA project SOLEUS aimed to develop a new approach of integrated countermeasure device in the shape of lower-leg boot-exoskeletons associated with 3D head mounted display. It focused primarily on the neuromotor and mechanical stimulation of the lower limbs that are the most heavily affected body parts while astronauts are exposed to microgravity. This approach is supported by immersive Virtual Reality (VR) technologies providing additional stimulation and information to the user, in order to increase the countermeasure efficiency. Compared to existing approaches for space countermeasure currently used on-board the ISS, the following benefits were expected:

- Improved mechanical stimulation of the lower leg segment and higher activation of the muscle-tendon unit (MTU) of the lower legs, with a focus on the spring-damper behavior and stiffness characteristics (optimized muscle energy storage).
- Virtual Reality (VR) for increased motivation (recreative, challenges), activation of the full functional tasks including neurologic transmissions and pathways (e.g. balance, locomotion, reflex, patterns generators). The VR allows also to trick human senses for increasing solicitation effect or for compensating the absence of other solicitations.
- Full orthosis controllability for advanced and tailored scenarios/exercises.
- Reduced foot print and mechanical isolation from the spacecraft (fully portable).
- Potential to be used in parallel to other activities and training sessions.

1.2 Main Achievements

This project developed an integrated system for neuro-musculo-skeletal countermeasure, in the shape of two lower-leg exoskeletons for ground demonstrator, associated with virtual reality immersion. The design was supported by modelling and simulation from the Anybody Simulation framework. It was used to compare several concepts of orthosis and also to derive design parameters and mechanical loads on the final selected design. The SOLEUS device has been validated on human subjects through a set of experimentation covering standard testing (isometric, isokinetic) and advanced scenarios with virtual reality (ball game, balance and posture control). Recommendations and lessons learned have been finally summarized to support next developments of equivalent systems.

1.3 Consortium

The project consortium includes two companies and one institute. Space Applications Services, as prime is responsible of the full system specification, design, integration and testing. It is supported by the Institute of Aerospace Medicine of DLR for medical expertise and performance of the scientific evaluation, Anybody Technology for modelling and simulation as support of the design phase, and the consultancy of Joseph McIntyre for topics related to neurophysiology.

2 SOLEUS Architecture and Design

Figure 2-1 represents the SOLEUS system architecture. It is composed of:

- Two lower-leg exoskeleton orthoses (left and right) enabling active torque feedback and motion control along the ankle (2 DoF, individually controllable).
- The controller PC, responsible for the high-level management of the orthoses (configuration, mode of operation, safety…), the computation of the low-level physics interactions of the scenarios (contact forces) and the communication with the VR simulator.
- The VR simulator that manages the subject's exercises, computes general physics and creates 2D (for screen display) and 3D rendering.
- An Oculus Rift 3D head mounted display (HMD) to display and immerge the subject in the 3D environment for the exercises.

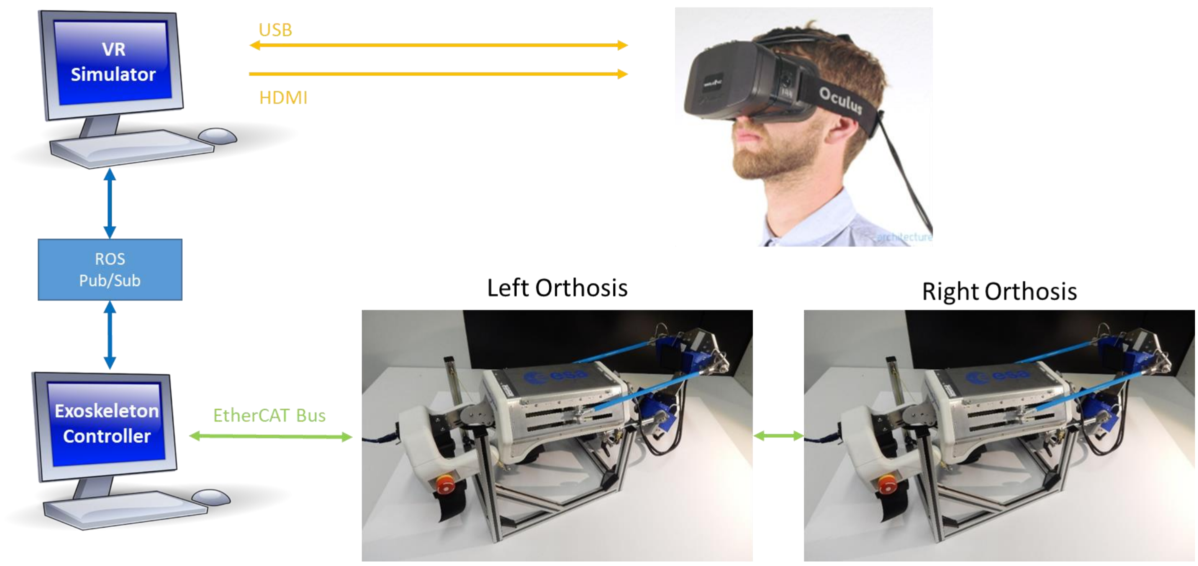

Figure 2-1: SOLEUS System Architecture

The technical orthosis specifications are provided in Table 2-1. For weight optimization and compactness, the orthoses are built from thin aluminium sheet structures, assembled with 3D rapid prototyping components, featuring adjustable mechanisms to fit most subject's sizes. Two high-power brushless DC actuators with gearbox connected to an offset crankshaft parallel mechanism offer high torque amplification in dorsi/plantar flexion when they move synchronously or in pronation/supination when they move in opposition (Figure 2-2). Incremental encoders (on each motor side), absolute angle sensors (on all active joints) and force sensors embedded in the transmission bars of the mechanism allow computing flexion and pronation motion and torques produced by the user on the orthosis. Communicating through EtherCAT, the low-level control boards and the exoskeleton controller enables active control of the ankle joints as feedback of the selected applications scenarios. Mechanical end-stops, foam padding and shin pads offer safety and comfort to the subject.

The VR simulator is running Unity3D and the eVRS framework (product of Space Applications Services) that allows scientists or practitioners to create and manage easily 3D medical scenarios, and to interface many different hardware components to be used during the experiments. The system allows connecting a 3D head mounted display (Oculus Rift) to render 3D worlds computed by Unity and to track user's head motion. The VR system is connected to the exoskeleton controller with ROS for exchanging control and telemetry data.

Table 2-1: SOLEUS System Specifications

SOLEUS Specifications	
Degrees of freedom	• Dorsi/plantar flexion (active, -40;+40) • Pronation/ supination (active, -30; +30) • Knee flexion/extension (passive, -90; +0)
Structure	• Thin Aluminium sheet • Alumide SLS 3D print • PA-GF SLS 3D print casing
Actuation / Peak torque	• 130Nm dorsi/plantar flexion • 80 Nm pronation/supination
Sensors	• Angle and Torque dorsi/plantar flexion • Angle and Torque pronation/ supination
Adjustment	• 10th percentile female to 90th percentile male
Ergonomics and comfort	• Nylon straps • Foam Padding • COTS shin pad
Weight	• 6.4 Kg
Interfaces / Framework	• ROS / EtherCAT, Unity3D and Occulus

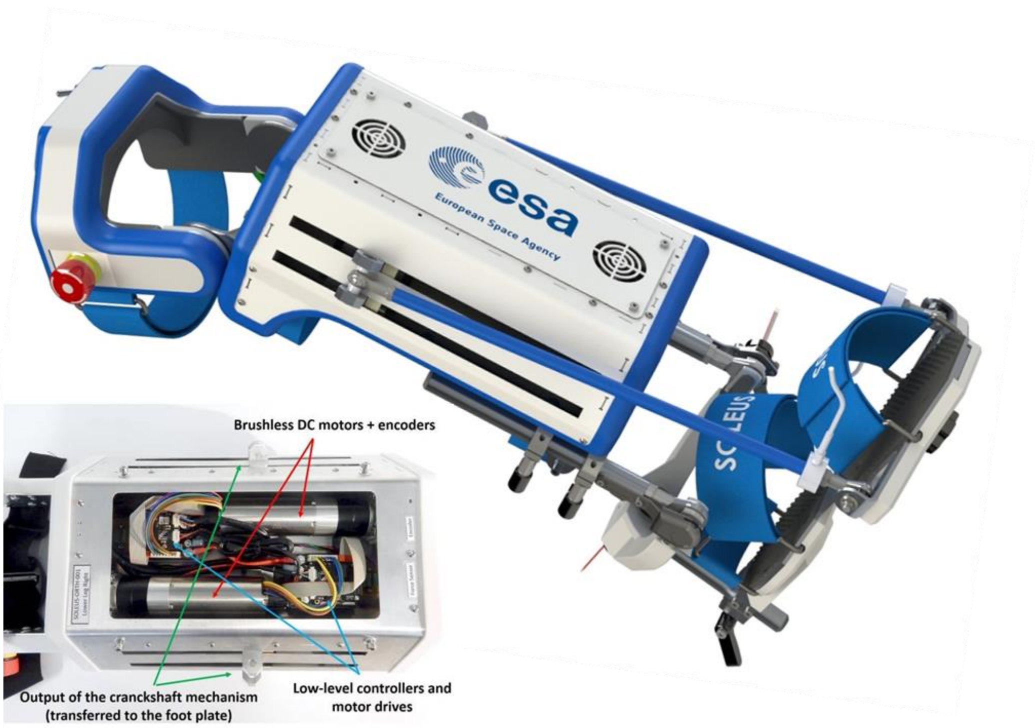

Figure 2-2: SOLEUS Design and Mechatronics Highlights

3 SOLEUS Modelling

The design process has been supported by the AnyBody Technology simulation framework. Based on a realistic model of the lower-leg human muscular-skeletal system and a model of the orthosis mechatronics design, this simulation demonstrated the ability of SOLEUS orthosis to generate proper muscular activation and interactions forces for the envisaged user's scenarios (Figure 3-1). The simulation has also been used to compare several initial concepts, derive design parameters and compute mechanical loads to populate finite element analysis computation.

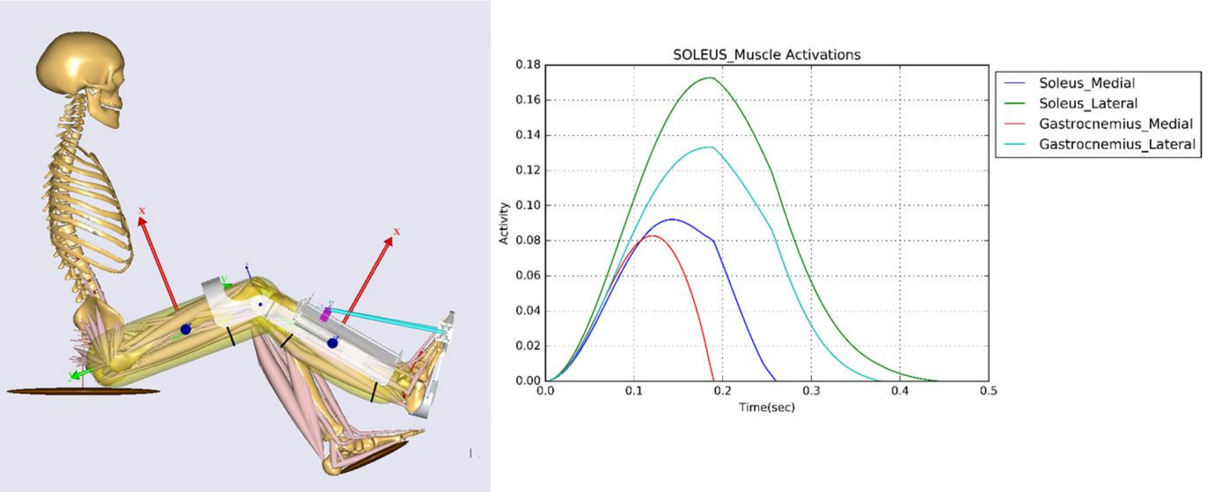

Figure 3-1: Musculo-skeletal simulation of the human ankle wearing the SOLEUS orthosis with the Anybody Modelling System

4 Scientific Evaluation

4.1 Purpose and Study Set-Up

The general purpose of the scientific evaluation was to validate the SOLEUS system on human beings and demonstrate its modes of action at physiological level. More specifically, the scientific study aimed at:

- Validating the main functions of the system and bringing evidence of the potential interests of exoskeletons as countermeasure devices.
- Evaluating the potential benefit of the Virtual Reality stimuli in countermeasure applications (e.g. increased stimulation).
- Comparing the SOLEUS system performance (including muscle activation) with standard scientific apparatus (e.g. Isomed 2000).
- Assessing human factors such as ergonomics and comfort.
- Analysing the effectiveness of the system (hardware, software) from subject and operator point of view.

The study has been conducted in the physiology laboratory of envihab at DLR, Cologne, on 15 subjects, who performed all SOLEUS scenarios described below. The ISOMED 2000 has been used as a reference test bench and also to support mechanically SOLEUS in a free floating configuration. Beside the sensors data measured on the orthoses, EMG signals of the lower-leg muscles have also been recorded.

Figure 4-1: SOLEUS Scientific Evaluation set-up and comparison with ISOMED 2000.

4.2 Scenarios and Results

As characterization and illustration of SOLEUS potentials for countermeasure applications and scientific purpose, several scenarios have been developed and tested during the scientific evaluation. They included standard isometric and isokinetic exercises, and more advanced scenarios using VR technologies.

4.2.1 Standard Isometric and Isokinetic Tests

The purposes of isometric and isokinetic trials were to determine maximum EMG amplitudes for normalization of other tests, and compare them with a standard medical device (Isomed 2000) both for muscle activity and ergonomics/comfort.

For isometric tests, the subject is asked to press with the foot as strong as possible (without overpassing pre-defined limits for the orthosis) in two different static positions of the knee joint. For the isokinetic test, the user is asked to try to move the orthosis as fast as possible, while the controller limits the velocity to a pre-defined value through the orthosis controller.

When subjects were allowed to perform maximum voluntary contraction, the torque levels and the patterns of muscle activation were similar between the two devices, showing that SOLEUS is a good candidate to perform these exercises. In the SOLEUS device, isometric and isokinetic plantar flexion at reduced torque levels resulted even in higher EMG amplitudes/torque in comparison with the MVC performed on the ISOMED. This could be explained as the subject needs to control his/her force (to not overpass SOLEUS limits), enabling more muscle contraction. For further experiments, we could envisage submaximal torques control on both devices for comparison.

4.2.2 Ball Kicking

In the ball kicking scenario, the subject, immerged in a virtual 3D training scene (Figure 4-2) is asked to push on balls coming down in contact with the foot (with the 1 DoF set-up of the orthosis). The purpose of this test was to investigate new approach of countermeasure exercises, to compare stimulation results with standard methods and to stress the spring/damping properties of the calf muscles and Achilles tendons. Although not done with the current setup, this scenario also enables muscle pre-activation investigation.

Figure 4-2 illustrates successive interaction contacts during a ball kicking session. The ball-kicking scenario allowed to stimulate strongly the lower-leg muscles group reaching almost 100% activation isometric MVC. With the set of parameters implemented, we were approaching the behaviour of physical hoping that is one of the possible training approach for countermeasure. This scenario is characterised by a big variety of parameters (physics, contact parameters, orthosis control) allowing a large panel of solicitations.

Tests results have been compared with and without virtual reality stimulations. Although we have observed some tendencies of higher solicitation with VR, the current set of experiments do not allow us to significantly confirm its effect. For future experiments, more tests subjects, a better focus of the experiment (less complex 3D environment) and a higher level of fidelity from the VR/orthosis interaction should be investigated.

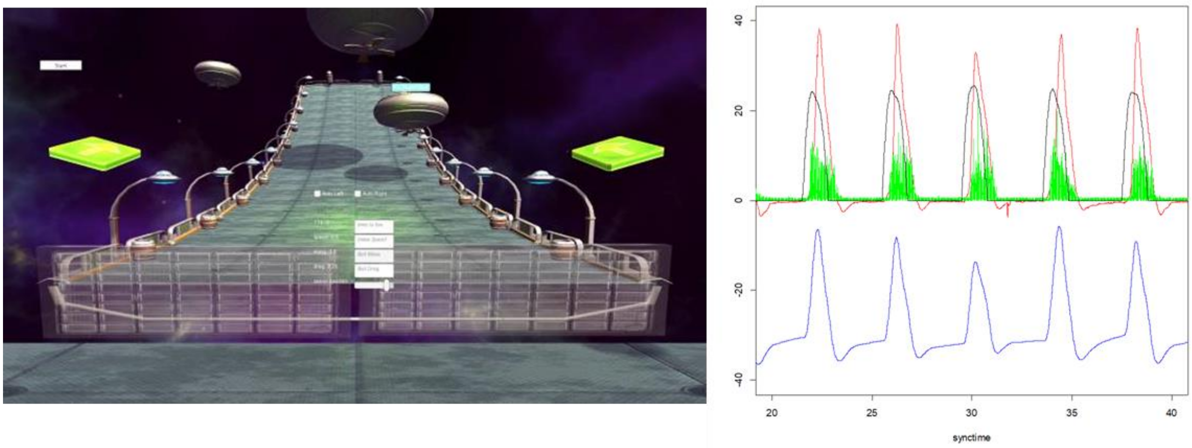

Figure 4-2: Ball Kicking 3D visualization and subject data measurements (blue: flexion angle, red: flexion torque, green: EMG soleus muscle)

4.2.3 2 DoF Balancing and Postural Control

As an illustrative experiment with SOLEUS, balance control exercises have been experienced by the subjects. These included 3D maze board game and ankle control under perturbation (target), around the 2 DoF of the ankle (Figure 4-3). The specific aim of such activities is to improve balance control and ankle stabilization. From EMG measurements, we have highlighted increase of ankle joint stiffness and controlled counter movements, showing the relevance of the approach.

We have also implemented tests around postural control (Figure 4-4). Mechanical stimulation associated with coherent (in the same direction) or incoherent visual cues through the 3D HMD were applied on the subject. We clearly highlighted effects of the postural instability on EMG signals as well as interactions between visual and mechanical perturbations. This experiment highlighted the potential for SOLEUS to support neurophysiological scientific experimentations.

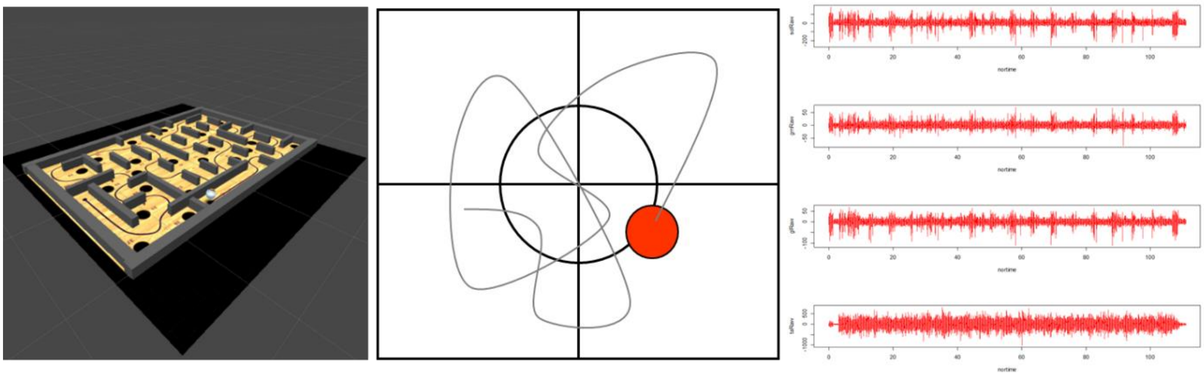

Figure 4-3: Balancing scenarios in 3D (maze) and 2D (target point under random perturbation), EMG recording during balance control

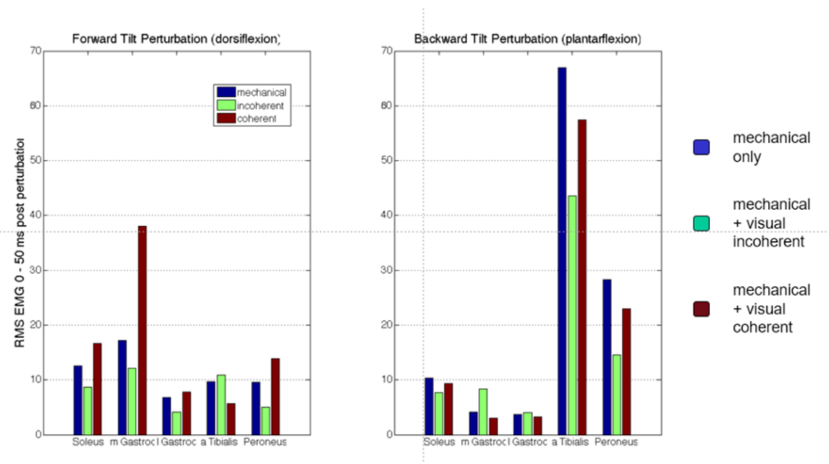

Figure 4-4: Postural control EMG comparison

5 Conclusions

The SOLEUS activity was successful in demonstrating the capability to use the SOLEUS device, and in general lower leg exoskeletons, in the context of space countermeasure. This prototyping activity has also highlighted the complexity of such developments, mainly related to user’s comfort and complexity of orthosis/VR/user interactions. The relation between training requirements (level of torque, required speed…) and needs of compactness and lightweight structure for flight models will be at the core of future developments.

At the end of the activity, we have compiled the potential future applications of SOLEUS both for space or ground applications. For space agencies, there is a strong interest for integrated, compact and multi-purpose devices able to improve countermeasure exercises. The SOLEUS project aimed on its own to address musculo-skeletal and neuro-muscular/vestibular aspects at the same time. SOLEUS is also a good candidate for further integration in other projects like multi-joint leg exoskeletons, which could then extend the performance of the system with more muscles activated or approaching better the full leg functionality. Finally, with all embedded sensors, SOLEUS can be envisaged as a compact measuring device that is currently lacking on ISS.

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