SOLEUS: ANKLE FOOT ORTHOSIS FOR SPACE COUNTERMEASURE WITH IMMERSIVE VIRTUAL REALITY

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ABSTRACT

This paper presents the SOLEUS project, which aims to design a new active foot orthosis associated with immersive virtual reality technologies, as an innovative countermeasure approach for astronauts in space. The paper introduces the problematics of space countermeasure and describes the expected benefits of the proposed technology. It details the system architecture, components and the simulation analysis that has been used to support the design process. Then, it summarizes the main results of the functional testing of the system. Finally, the scientific evaluation strategy for the validation of the product is introduced.

1. INTRODUCTION

During spaceflight, the human body is subject to physiological adaptation to the microgravity environment. Although some effects, like vestibular disorders, lead to temporary discomfort for 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 issues met by astronauts in microgravity. 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 on-going ESA project SOLEUS aims to develop a new approach of integrated countermeasure device in the shape of a lower-leg boot-exoskeleton associated with 3D head mounted display. It focuses primarily on the neuromotor and mechanical stimulation of the lower leg body segments that are the most heavily affected body parts while astronauts are exposed to microgravity. This approach is supported by immersive Virtual Reality (VR) technologies aiming at providing additional stimulation and information to the user, in order to increase the countermeasure efficiency. This paper presents the status of the project, describing the expected benefits of the device, the system design, supported by the use of musculo-skeletal simulation tools, and the results of the functional testing.

2. SOLEUS PROJECT EXPECTED BENEFITS

The SOLEUS project is mainly characterized by the association of active ankle orthosis for each leg and an immersive virtual reality display. Compared to existing approaches for space countermeasure currently used on-board the ISS, the following benefits are expected:

- Activation of the muscle-tendon unit (MTU) of the lower legs as a whole, with a focus on the spring-damper behavior and stiffness characteristics of the MTU [1], that is not fully addressed by the current use of the treadmill or body press [2]. Optimization of energy storage in the MTU has a direct impact on the longitudinal bone force loading during specific motion (jumping, running).

- The use of the VR to create scenarios addressing not only the pure muscle atrophy but also the full functional task including the neurologic transmissions [3]. The system can be used to stimulate different neurological pathways (e.g. balance, locomotor, reflex, patterns generators) to increase the number of motor units activated (MU, association of a neuron and muscle fiber). That can also include tricks and cheats to increase the effect or compensate for the absence of other solicitations (e.g. feel of the gravity vector).

- Increased motivation by using the VR for displaying challenging and recreative adapted scenarios. Experiments have suggested that outcomes are better when practice is task oriented, repetitive and adapted to the user [4].

3. SOLEUS ARCHITECTURE AND DESIGN

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

- Two lower-leg exoskeletons orthoses (left and right) with active torque feedback along the ankle motions;
- The Exoskeleton Controller, responsible for the high-level management of the orthoses, the computation of the low-level physics and the communication with the VR Simulator;
- The Virtual Simulator (VR) that manages applicable scenarios, compute general physics and creates 2D (screen display) and 3D (Occulus Rift) rendering / GUI interfaces.

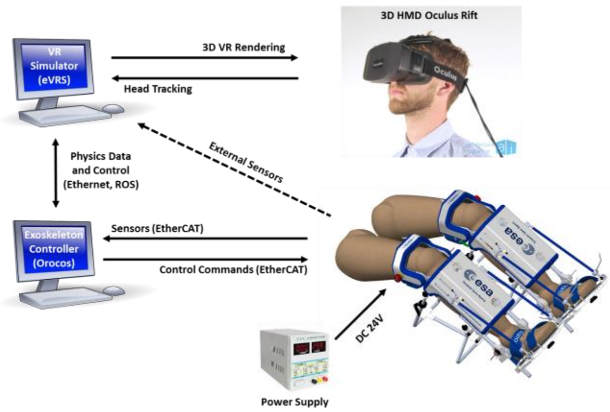

Figure 1. SOLEUS system architecture overview

3.1. Lower Leg Orthosis Mechatronics

The SOLEUS system includes two portable lower-leg orthosis (left and right) as shown in Figure 2. Their purpose is to measure the motion and interaction forces of the user and to implement active feedback based on the selected countermeasure exercises. They enable active control of the ankle joint in the flexion/extension and pronation/supination motions.

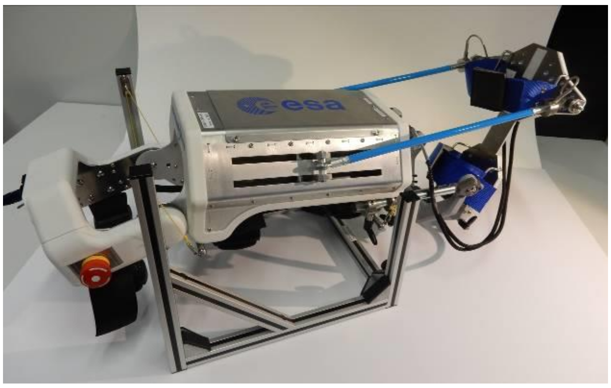

Figure 2. SOLEUS exoskeleton orthosis

Each orthosis is composed of the following elements (see Figure 3 for inner mechatronics integration view):

- Robust and lightweight mechanical structure based on thin metal sheets design and rapid prototyping components (SLS and FDM) with adjustable mechanisms to fit 10-90 percentile range;
- Two high power brushless DC actuators with gearbox connected to an offset crankshaft mechanism to reach a high torque amplification. They drive a parallel mechanism connected to the foot plate. It enables dorsi/plantar flexion if both motors work synchronously or pronation/supination if they work in opposition;
- Incremental encoders (on motor side), absolute angle sensors (on active joint side) and force sensors embedded in the transmission bars of the mechanism that allows computing flexion and pronation torques produced by the user on the system;
- Low-level control and communication boards with motor drive, based on Synapticon product range;
- Adjustable hardware end-stops located in the crankshaft mechanism;
- Wide user fixations on the back-leg and on the foot that transfer active loads to the user;
- Power bus of 24V with medical grade power supply;
- Full casing to protect all drive elements, cabling and electronics.

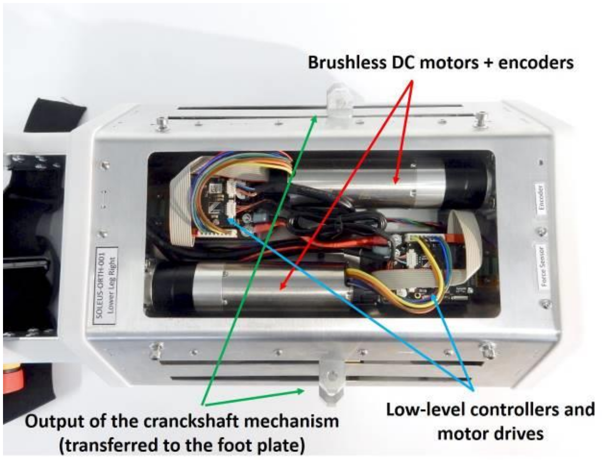

Figure 3. Inner view of SOLEUS orthosis actuation and control integration

Table 1 provides the main specifications of the SOLEUS orthoses. Due to initial scenario requirements (based on jumping exercises constraints), the system has been designed to reach high level of torque, up to

130Nm in the dorsi/plantar flexion. This has an influence on the total weight of the system, mainly driven by the actuation and transmission system and the required structure integrity.

Table 1. SOLEUS orthosis specifications

Parameters	Values
Dimensions	65 x 22 x 33 cm
Mass	5.9Kg per orthosis
Adjustment	10^{th} percentile female to 90^{th} percentile male
Degrees of freedom	• Dorsi/plantar flection (active) • Pronation/ supination (active) • Knee flexion/extension (passive) • Ab/adduction (fixed after setup)
Maximum torque	• 130N.m dorsi/plantar flexion • 80 N.m pronation/supination
Angle range	• Dorsi/plantar flection (-40; +40) • Pronation/ supination (-30; +30) • Knee flexion/extension (+0; -90)
Torque measurement	• Dorsi/plantar flection • Pronation/ supination
Angle feedback	• Dorsi/plantar flection • Pronation/ supination

3.2. Controller and Data Interfaces

The main purpose of the exoskeleton controller is to perform high level control and safety validation of the orthosis. Based on the implementation of ROS nodes (running on Ubuntu 14.04), it includes three main components:

- An admittance controller, running at 1 kHz, that derives position set-points from user/system interaction measurements and scenarios data. These set-points are sent to the low-level control boards running a position controller. Admittance control has been selected due to the high natural dynamics of the system;
- A state machine used to control more efficiently all the configurations and running steps of the system;
- A low-level physics simulation for applicable scenarios that allows high rate computation and stable interaction;
- Safety check on different variables to either constraint the user (e.g. virtual walls) or to disable actuation power (e.g. over limit range).

The exoskeleton controller also implements an EtherCAT master application to drive the EtherCAT data bus that interconnects the controller with the embedded boards (Figure 4). The communication with the VR simulator is done through the standard ROS publish/subscribe mechanism.

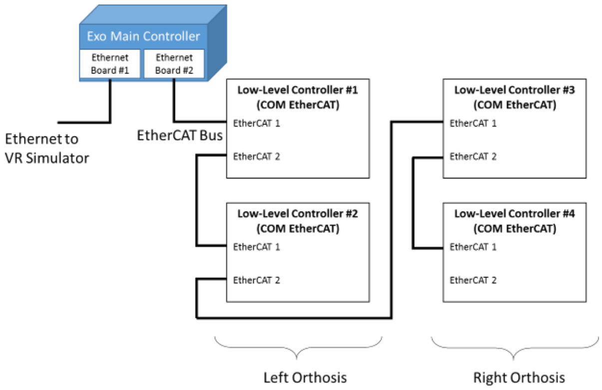

Figure 4. Soleus control architecture and communication

3.3. Virtual Simulator and Scenarios

The VR simulator is responsible to simulate high level physics (not directly related to the interaction with the foot orthosis) of the exercises scenarios and to create the rendering of 3D world environment in which the user will be immersed. It is also used to provide standard GUI interface to easily control the full system.

The VR simulator is composed of a computing unit running Unity3D [5] and the eVRS framework (produced by Space Applications Services) that allows standard physicians 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 the 3D world computed by Unity and to track user's head motion. The VR system is connected to the exoskeleton controller through ROS to exchange measured and control data. The system can also be interfaced with medical instrumentation (e.g. EMG sensors) to measure muscle activity during operations (for medical evaluation).
Different scenarios have been defined to make the evaluation of the Soleus system:

- Isometric: standard physiological test where the user is asked to push on the foot plate in a predefined position angle;
- Isokinetic: standard physiological test where the user is constrained to a maximum speed while moving. That test allows to check the torque generation capability on the full motion range;
- Ball kicking (Figure 5): 3D rendered test where the subject is asked to push on virtual balls that come in contact with the foot. This test allows analysing muscle pre-activation (from the link with the visualization), testing reaction time or stimulating the spring/damping effect of the lower-leg muscles (with several ball contacts iterations)

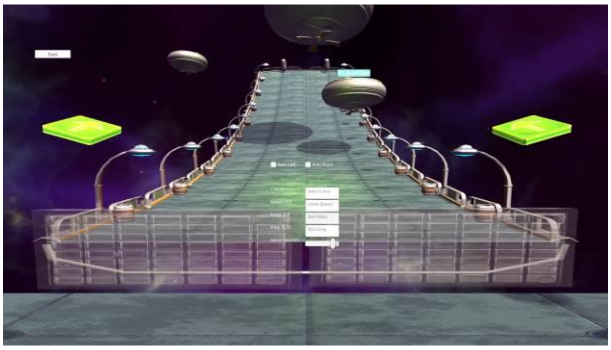

Figure 5. 3D rendering of the Ball Kicking Simulation Environment (in which the user is immerged with the 3D HMD).

- Balancing (Figure 6): represented here by an equilibrium board game, it allows to tests balancing motion with the 2 ankle DOF simultaneously and the relation with the virtual rendering.

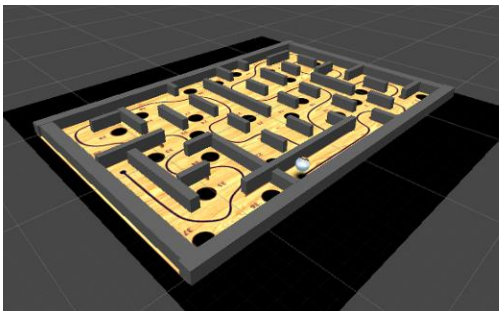

Figure 6. 3D rendering of the balancing scenario

4. MUSCULO-SKELETAL SIMULATIONS

The design process has been supported by the AnyBody Technology inverse dynamics software [6]. Based on a realistic model of the lower-leg human muscular-skeletal system and a model of the mechatronics design, we demonstrated the ability of the SOLEUS orthosis to generate the proper muscular response from typical user's scenarios (Figure 7). The simulation has also been used to derive the mechanical loads for finite element analyses and mechanical design optimizations.

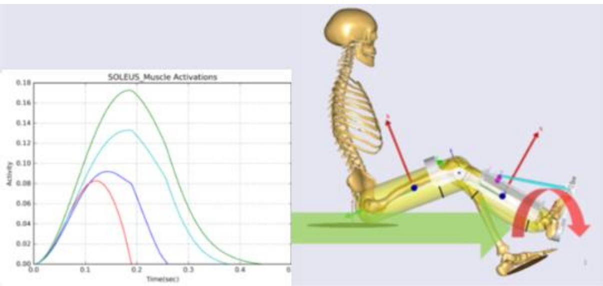

Figure 7. Muscular-skeletal simulation of a human ankle wearing the SOLEUS orthosis under load scenario, output of the muscular response under activation

5. FUNCTIONAL TESTING

An initial test phase has been conducted in order to:

- Calibrate and optimise the control parameters;
- Assess the functions, characteristics and performances of the devices;
- Assess the hardware, low-level and high level software safety features;
- Perform a preliminary usability and comfort analysis.

The following picture illustrates initial testing of simultaneous control of the orthosis and VR rendering with the user laying on a bed in order to better simulate the absence of gravity vector (mainly related to the feeling inside the 3D world).

Figure 8. Initial integrated tests between the exoskeleton and the VR rendering.

The different scenarios have been functionally tested and are illustrated in the following pictures.

Figure 9 shows the flexion angle set-point and measurement when the operator selects different target set-points where the user will be able to make the isometric test. When the target is defined, the system follows a cubic trajectory with smooth speed transition.

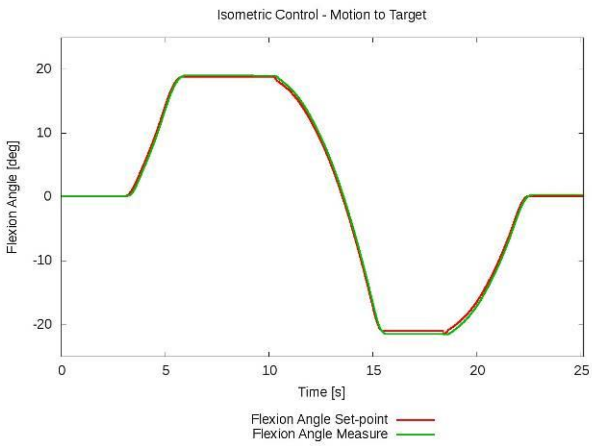

Figure 9. Flexion angle and set-point during Isometric target motion.

Figure 10 illustrates the isokinetic scenario. 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 admittance controller. The curve highlights two different phases with the first one limited at 30 deg/s and the second at 1 deg/s. We can observe the torque applied by the user that shows that he is pushing/pulling strongly on the foot plate.

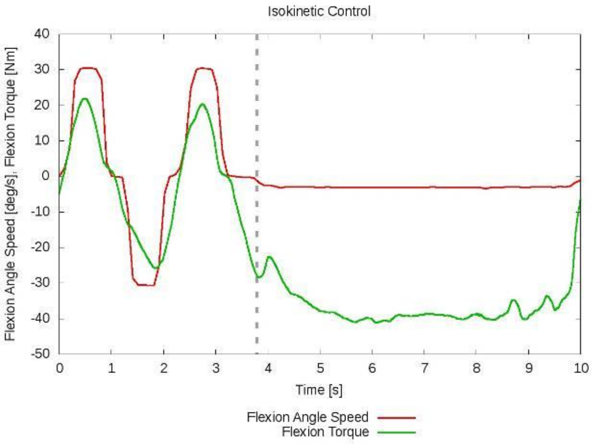

Figure 10. Flexion angle speed and torque during isokinetic experiment (limit at 30 deg/s and 1 deg/s)

Figure 11 illustrates the contact interaction when a virtual ball is hitting the foot plate in the ball kicking scenario. Here also the admittance controller is implemented. We can highlight the reaction time of the user (green curve) after the ball created an interaction torque (blue curve). The purpose of the scientific evaluation will be to optimize scenarios parameters (ball mass, stiffness, damping, admitance parameters, use of 3D/visual feedback) in order to improve the efficiency of this experiment.

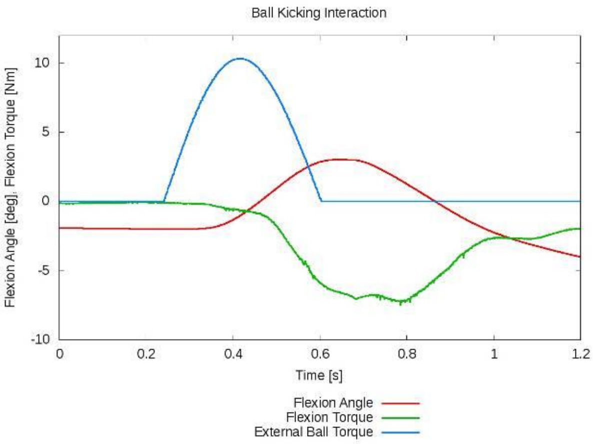

Figure 11. Flexion angle and torque measurement during a ball kicking experiment, when a virtual ball hits the user foot.

For the balancing scenario, two experiments have been conducted. The first one was based on the 2DOF equilibrium board game. It showed the capability to control the motion of a ball along a path while avoiding holes. The second experiment, focused on the plantar/dorsi flexion, was simulating an unstable body equilibrium, associated with visual 3D cues. We highlighted the capability for the system to create reflex motion on the lower leg when the user had the feeling to fall down.

6. SCIENTIFIC EVALUATION

The SOLEUS system is currently deployed in the Envihab: (DLR) to perform a scientific evaluation (Figure 12). The purpose is to validate the main functions of the system, focusing on the good synchronization between the mechatronics and virtual reality and bring in evidence the potential of the system as an efficient countermeasure solution. More precisely the goal is to obtain evidences of the activation of the spring-damper behaviour of the MTU, as well as increased EMG amplitude signal by the use of the VR rendering. The above mentioned tests will be conducted on 20 subjects to assess the expected benefits, while analysing risks and improvements to be taken into account in the next generations of the device. For standard isometric and isokinetic tests, the system will be compared with commercial equipment (e.g. Isomed 2000).

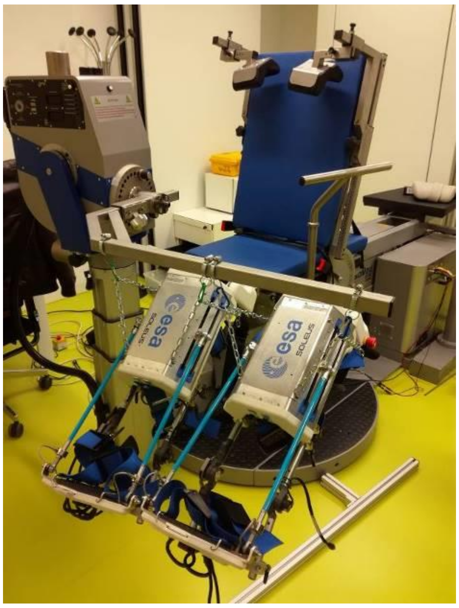

Figure 12. SOLEUS system deployed in the Envihab: (DLR) in parallel with the ISOMED 2000, for scientific evaluation

7. CONCLUSIONS

This paper presented the SOLEUS system as a wearable technology for the emerging applications of countermeasure for astronauts in space. This technology has also potential for non-space applications such as rehabilitation and healthcare.

The experiments performed during the functional testing highlighted that the SOLEUS system can potentially be used for a wide variety of stimulation, from standard physiological testing to more gaming scenario or reflex generation. The scientific evaluation will have to provide more precise conclusions based on the use of external EMG measurements.

The current design is a first prototype that will have to be improved and adapted for future space applications. The main adaptation should be the reduction of the maximum output power in order to reduce weight and volumes, in association with a selection of compatible applications. Regarding user comfort and system usability, although the current status is satisfying, we have already highlighted some improvements to be implemented in the next generation, as position of cable interfaces, adjustments mechanisms or GUI interfaces.

8. ACKNOWLEDGMENT

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9. REFERENCES

1. D. Farris, B. Robertson and G. Sawicki, Elastic ankle exoskeletons reduce soleus muscle force but not work in human hopping, J Appl Physiol 115: 579–585, 2013.

2. Alkner BA and Tesch PA. Efficacy of a gravity-independent resistance exercise device as a countermeasure to muscle atrophy during 29-day bed rest. Acta Physiol Scand 181: 345-357, 2004a.

3. Chopard A, Hillock S, Jasmin BJ. Molecular events and signalling pathways involved in skeletal muscle disuse-induced atrophy and the impact of countermeasures. J Cell Mol Med 13: 3032-3050, 2009.

4. Levin, M. et al. Virtual Reality Environments to Enhance Upper Limb Functional Recovery in Patients with Hemiparesis, book chapter "Advanced Technologies in Rehabilitation", 2009.

5. Unity3D: https://unity3d.com/

6. M. Damsgaard, J. Rasmussen, S. T. Christensen, E. Surma, and M. De Zee, "Analysis of musculoskeletal systems in the AnyBody Modeling System," Simulation Modelling Practice and Theory, vol. 14, pp. 1100-1111, 2006.