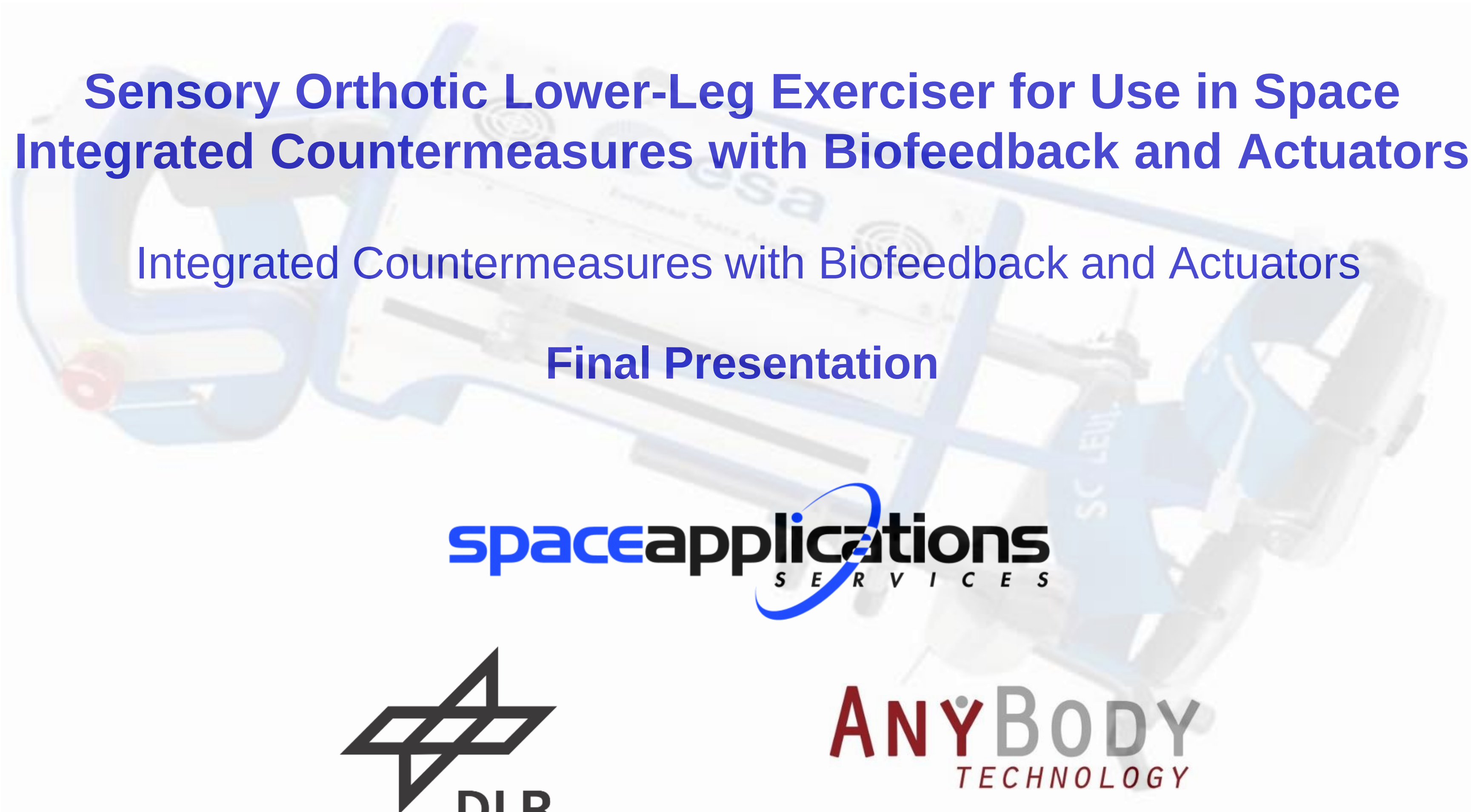
SOLEUS



Sensory Orthotic Lower-Leg Exerciser for Use in Space Integrated Countermeasures with Biofeedback and Actuators

Integrated Countermeasures with Biofeedback and Actuators

Final Presentation

Agenda & Outline

- General Introduction and Motivations
- Part 1 - Scientific and Technical Background
- Part 2 - Concepts, Detailed Design and Integration
- Part 3 - Scientific Evaluation
- Part 4 - Recommendations and Perspectives
- Open Discussion

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SOLEUS Project Summary Sheet

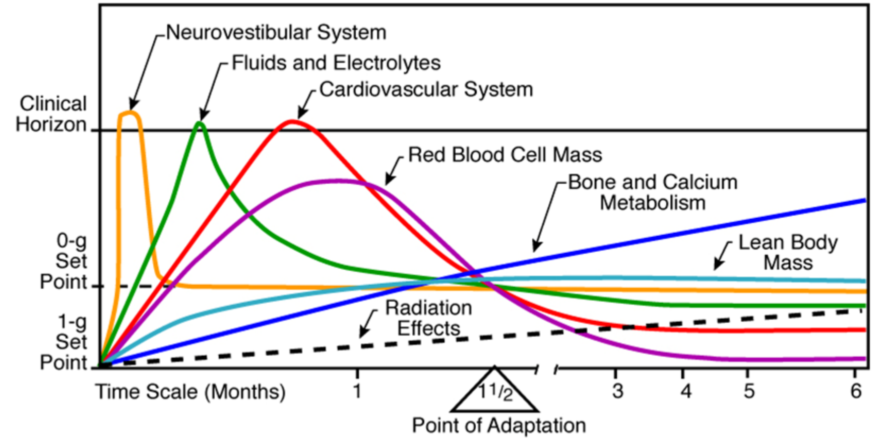
- 24 months TRP ESA study
- Consortium:

Consortium Partner	Position	Main Task	Acronym	Logo
Space Applications Services NV	Prime	Project management, system specification, concept, detailed design and integration, support to scientific evaluation and project recommendations	SA	
DLR – Institute of Aerospace Medicine	Subcontractor	Support and expertise to all project phases for biomechanics, physiology and body deconditioning, preparation, performance and analysis of the Scientific Evaluation	DLR	
Anybody Technology	Subcontractor	Modelling and simulation of SOLEUS exoskeleton and human body interaction in support to concept and design phase	ABT	
Dr.Joseph McIntyre	Consultancy	Expertise in neurophysiology, human perception in microgravity, support to system evaluation	JcI	

Project Motivation and Problem Statement

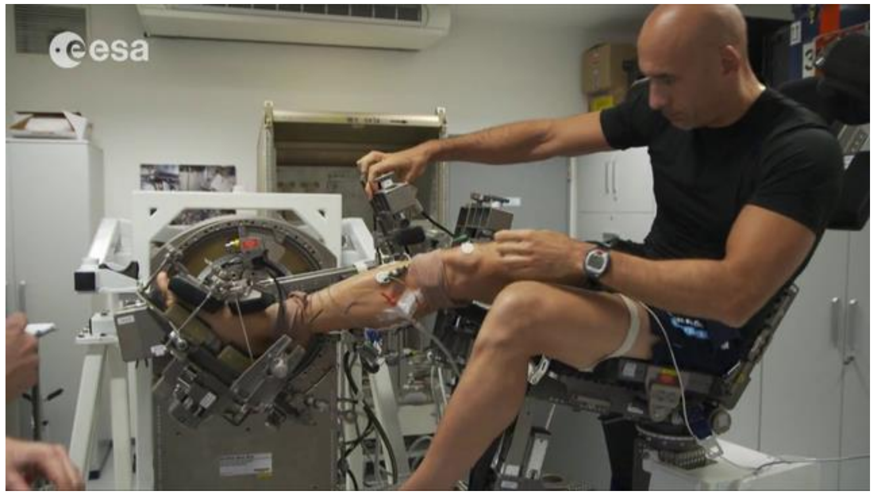
During space fight, the human body is subject to physiological adaptations:

- Vestibular disorders,
- Mineral bone loss,
- Muscle atrophy…
- Lower leg body is the most heavily affected.



Current limitations of existing systems:

- Heavy, complex and bulky structures
- Still partially mitigate deconditioning
- “Uni-functional” and low versatility



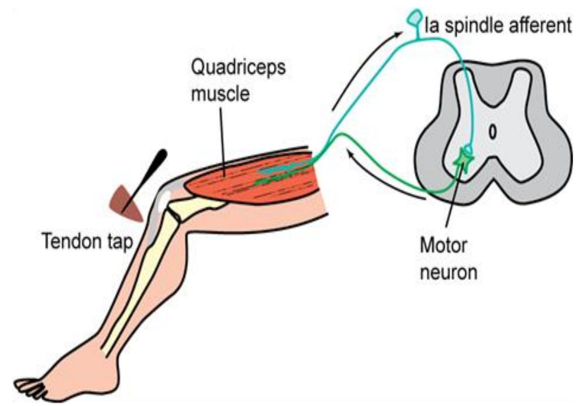
ESA Luca Parmitano training on the MARES machine. Credit ESA

SOLEUS Approach and Expected Benefits

Approach: integrated countermeasure + immersive stimulation

- Mechanical stimulation of the lower leg segment
- VR HMD for improved stimulation, multi-purpose and serious gaming
- Activation of the full functional task including neurological pathways: balance, locomotor, reflex, pre-activation, patterns generators,
- Increase the number of motor units activated (muscle fiber + neuron)
- Reduced foot print and mechanically isolated device
- Potential to be used in parallel to other activities / training

Lower leg calf muscles

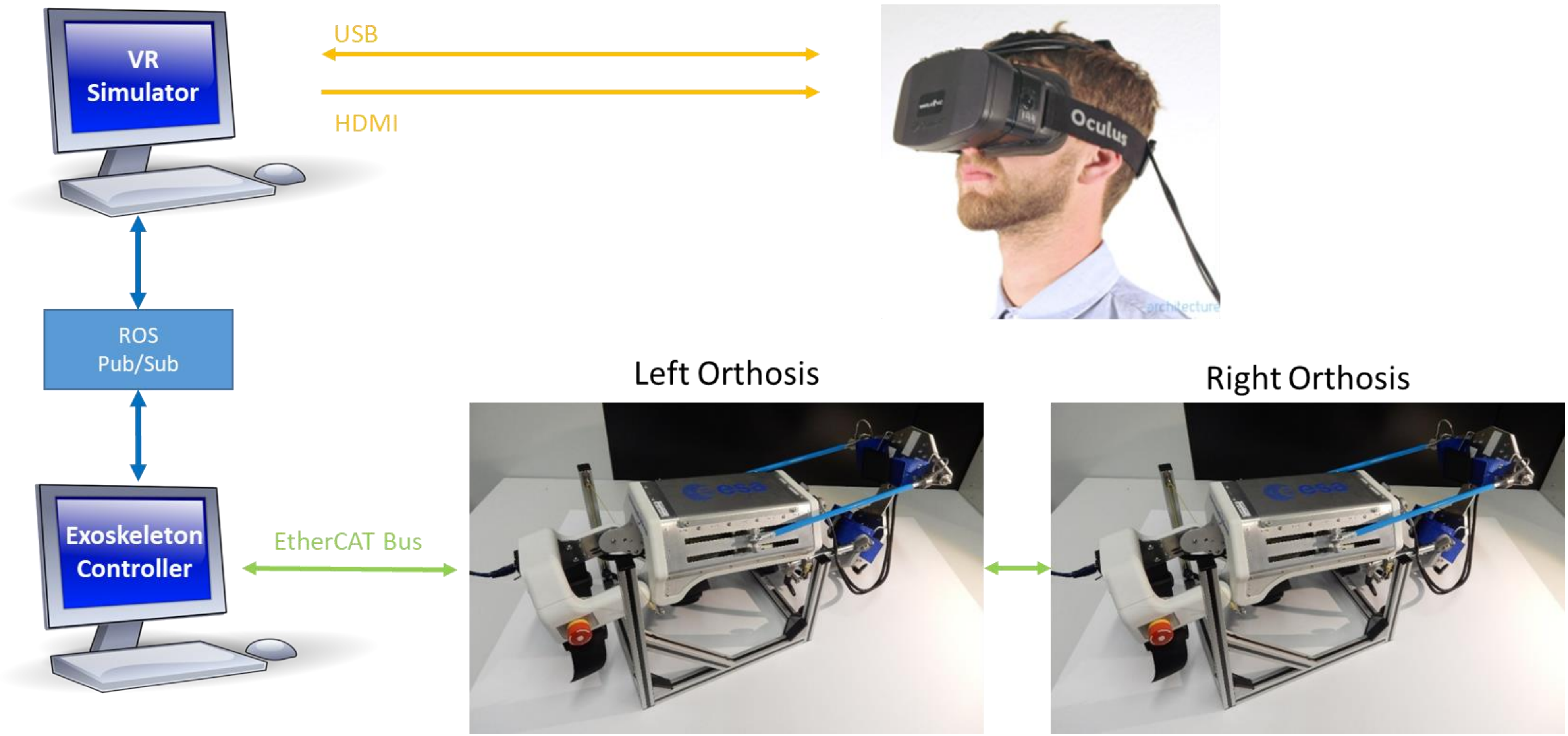


Neural pathway activation (from Squire et al.)

SOLEUS Project Objectives

- To develop and validate an integrated system for neuro-musculo-skeletal countermeasure systems, in the shape of a functional lower-leg exoskeleton ground demonstrator
- To validate the system on human beings and to demonstrate its modes of action at physiological level during a Scientific Evaluation
- To provide recommendations for future developments and propose preliminary flight concept

SOLEUS System Overview



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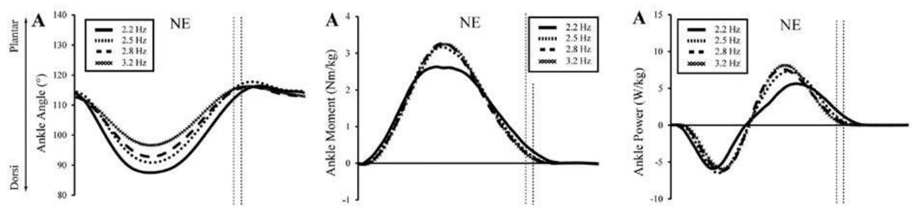
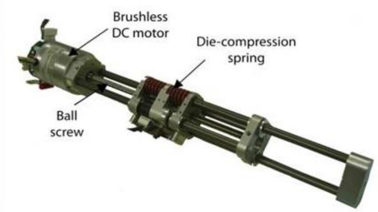
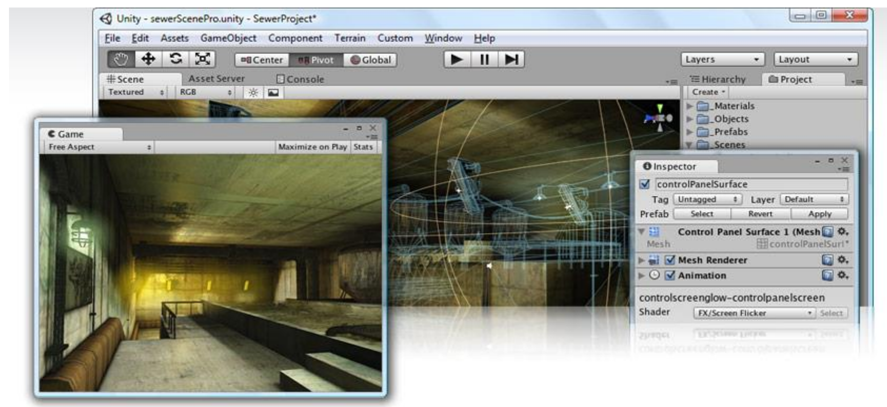
State of the Art and Scientific Background Analysis

- Provide a survey of the relevant scientific and technical topics related to the SOLEUS project
- Supported by a literature review and Team workshop
- Topics addressed:
  - Weightlessness effects on the lower-leg and countermeasure
  - Mechatronics and exoskeletons
  - Virtual reality and simulation support tools

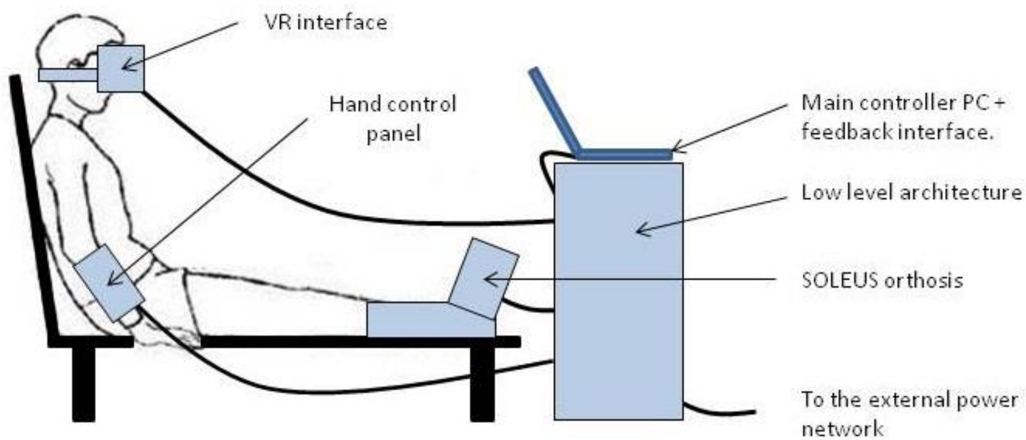


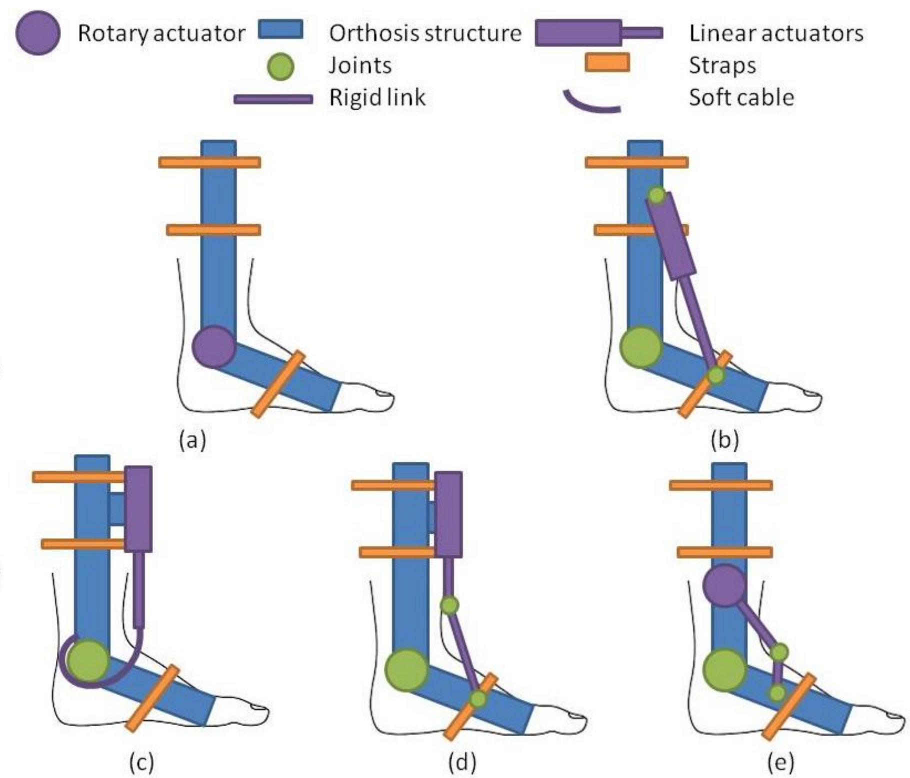




Requirements and User Scenarios Analysis

- Requirements analysis (functional, performance, operational, human factors, safety,…)
- User scenarios selection and definition (isometric, isokinetic, ball kicking, balancing)
- Initial concepts and design strategies comparison





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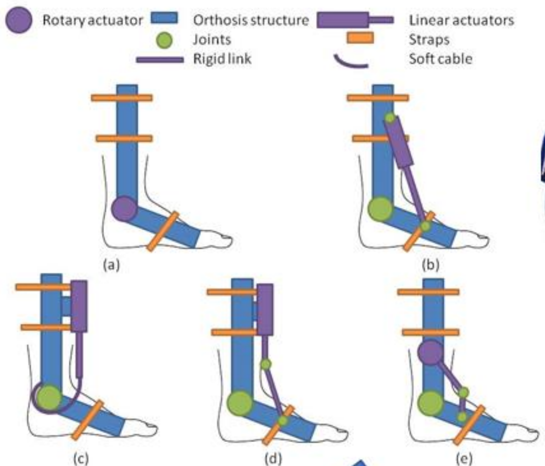
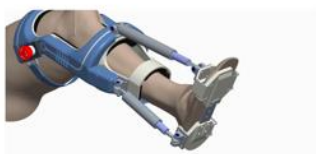
SOLEUS System Design Overview



WP1 – Scientific and Technical Background

WP4 – Detailed Design

WP5 - MAIT



(A) Semi-Parallel Concept

(B) Inline Parallel Concept

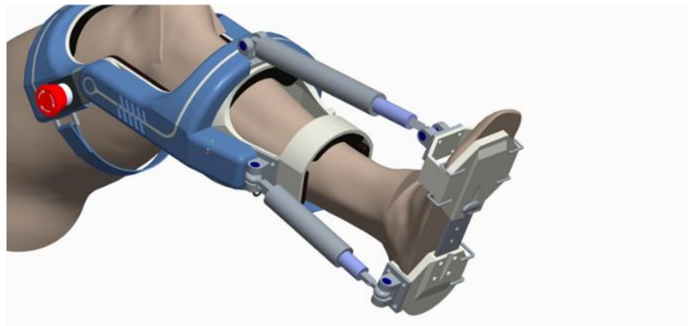
(C) Offline Parallel Concept

WP3 – System Concepts

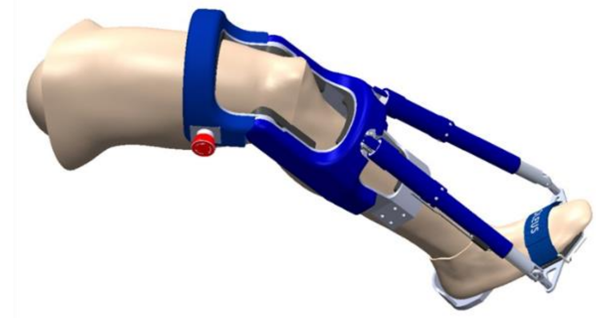
SOLEUS - System Concepts

Advanced concepts of ankle foot exercisers:

Semi-Serial:
- Linear actuator on front + on the side
- Motor moving with foot

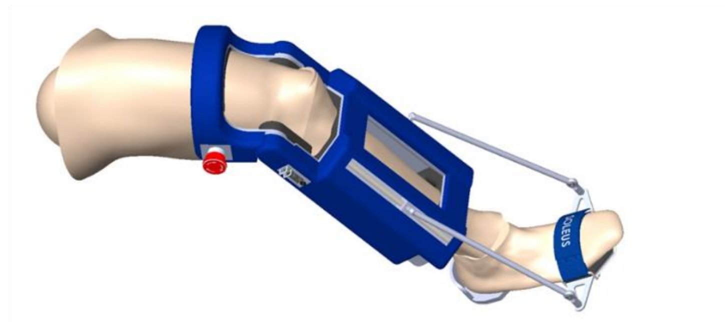


(A) Semi-serial Concept



(B) Inline Parallel Concept

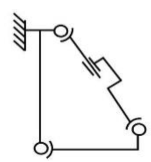
Inline Parallel:
- Both linear actuators on front
- Motor moving with foot



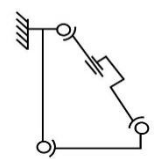
(C) Offline Parallel Concept

Offline Parallel:
- Both linear actuators on front
- Motors fixed on structure

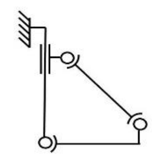
All concepts have been simulated by ABT for efficiency analysis.



Semi serial kinematic model



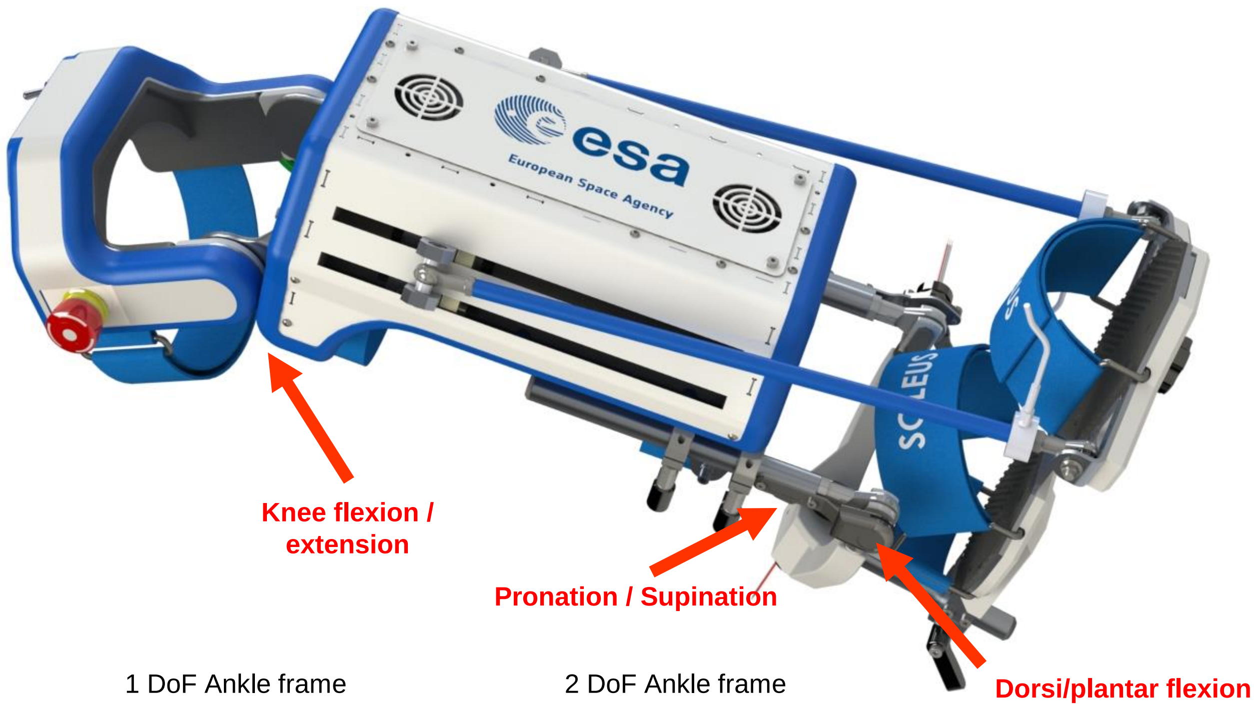
Inline parallel kinematic model



Offline parallel kinematic model

Lower Leg Exoskeleton

Specifications	
Degrees of freedom	• Dorsi/plantar flexion (active) • Pronation/ supination (active) • Knee flexion/extension (passive)
Angle range	• Dorsi/plantar flexion (-40; +40) • Pronation/ supination (-30; +30) • Knee flexion/extension (+0; -90)
Maximum peak torque	• 130N.m dorsi/plantar flexion • 80 N.m pronation/supination
Torque measurement	• Dorsi/plantar flexion • Pronation/ supination
Angle feedback	• Dorsi/plantar flexion • Pronation/ supination • Knee flexion/extension
Adjustment	10^{th} percentile female to 90^{th} percentile male
Weight	6.4 Kg



1 DoF Ankle frame

2 DoF Ankle frame

Lower Leg Exoskeleton

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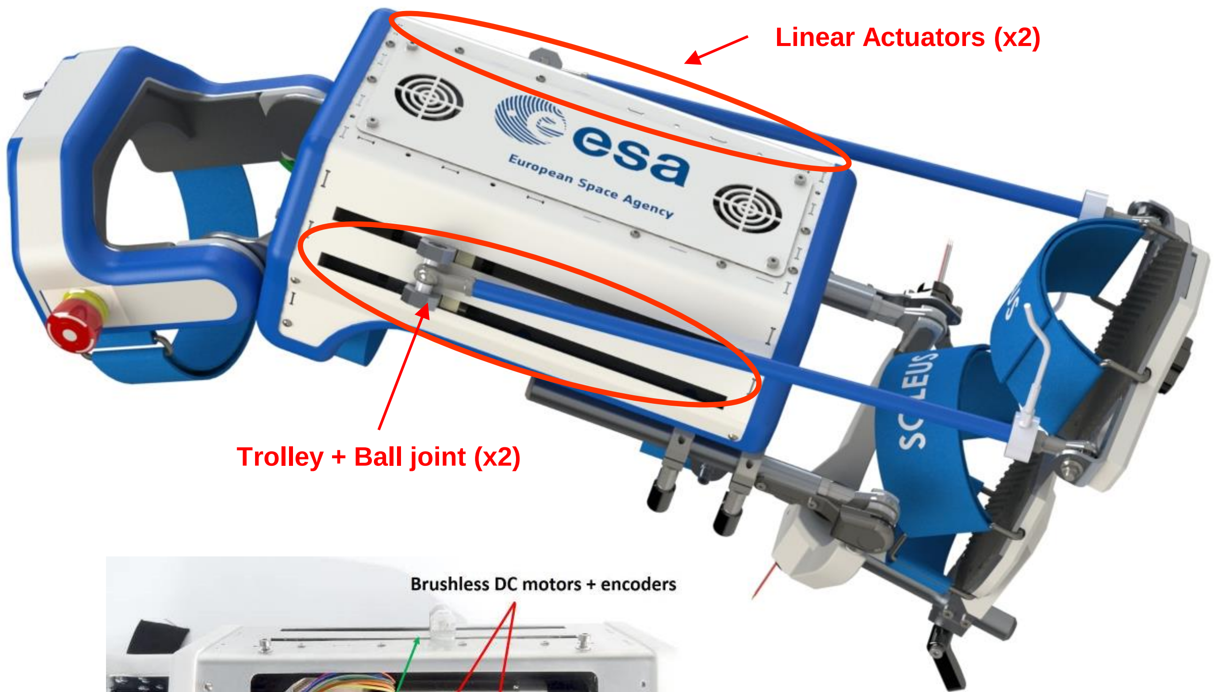

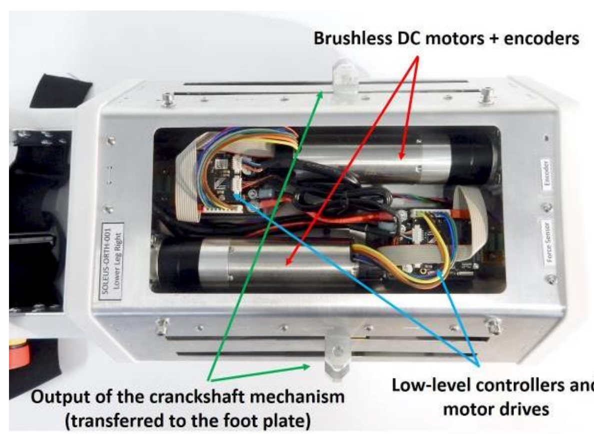

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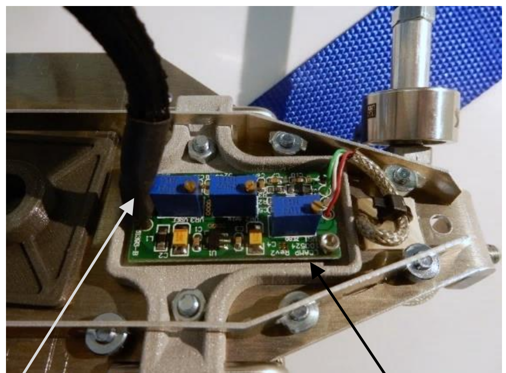

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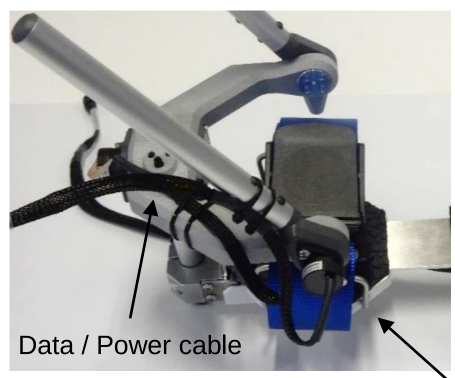
Weight	6.4 Kg

Absolute position encoder (x3)



Absolute angle sensor

Lower Leg Exoskeleton

Specifications	
Degrees of freedom	• Dorsi/plantar flexion (active) • Pronation/ supination (active) • Knee flexion/extension (passive)
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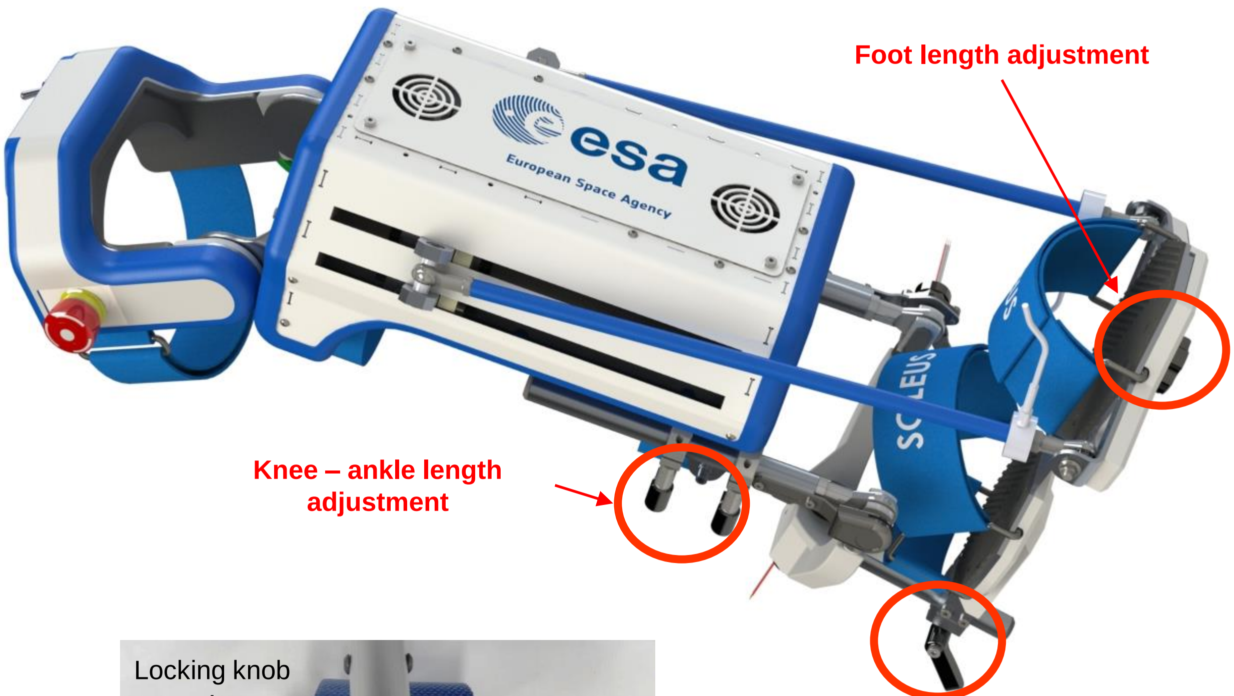
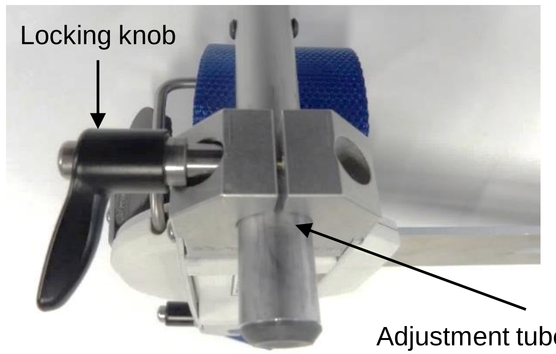
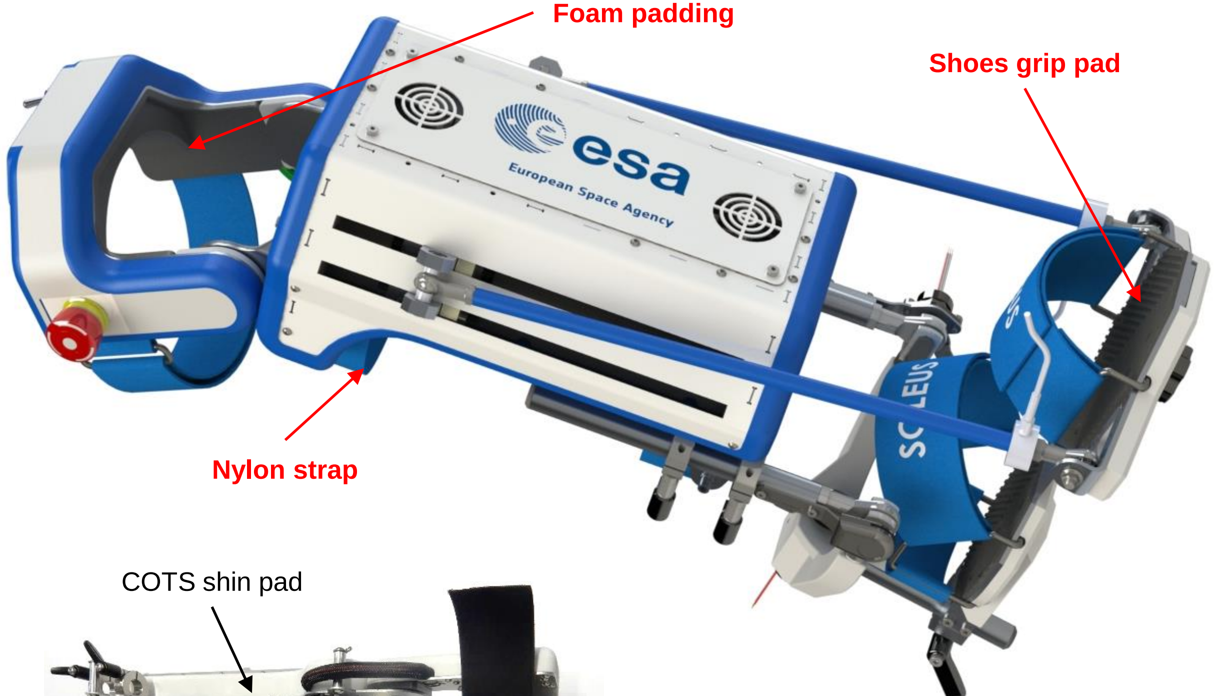
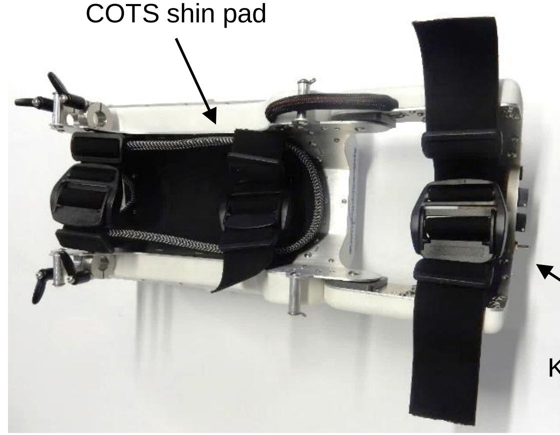




Lower Leg Exoskeleton

Mechatronics	
Ergonomics & Comfort	• Nylon straps • Foam Padding • COTS shin pad
Structure	• Thin Aluminium sheet • Alumide SLS 3D print • PA+GF SLS 3D print casing
Control & Electronics	• Synapticon motor drivers • ROS • EtherCAT
VR	• Oculus rift HMD • Unity





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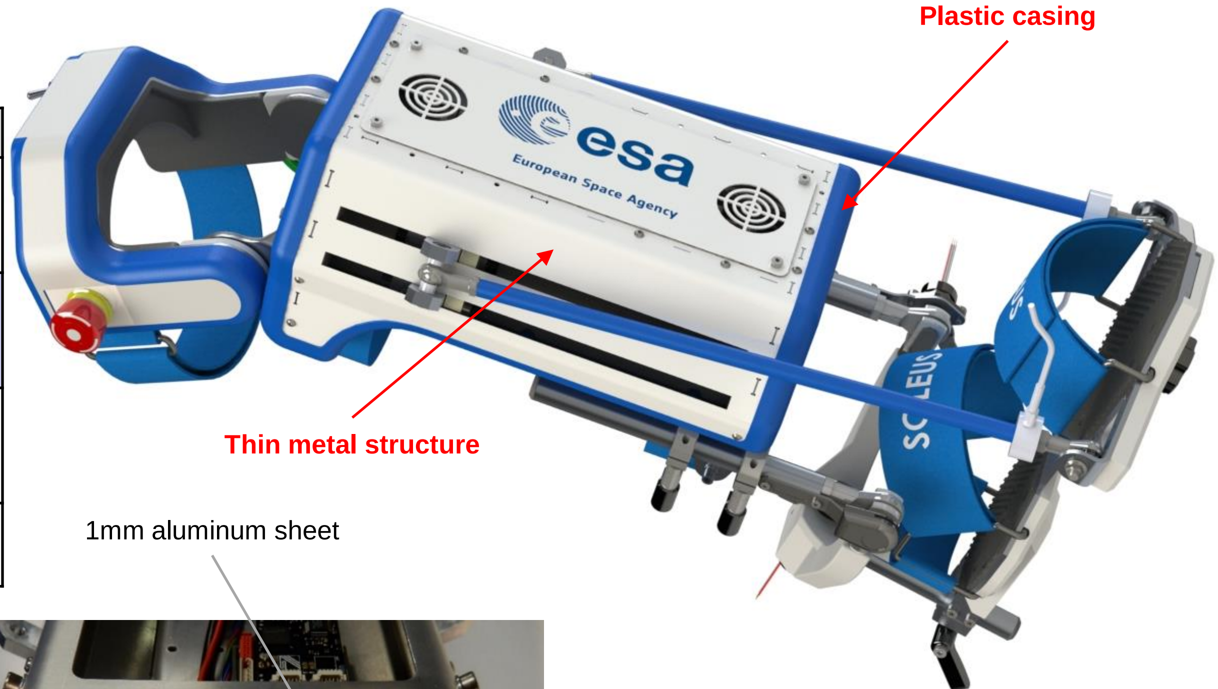
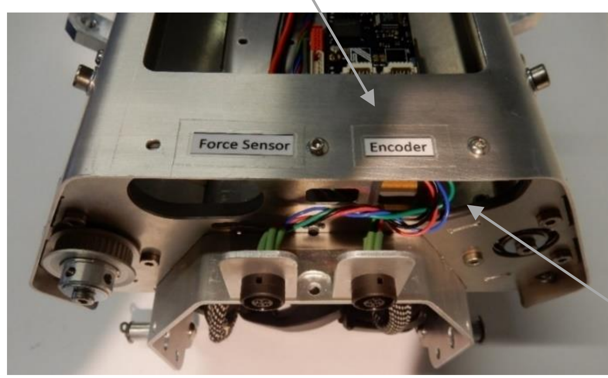
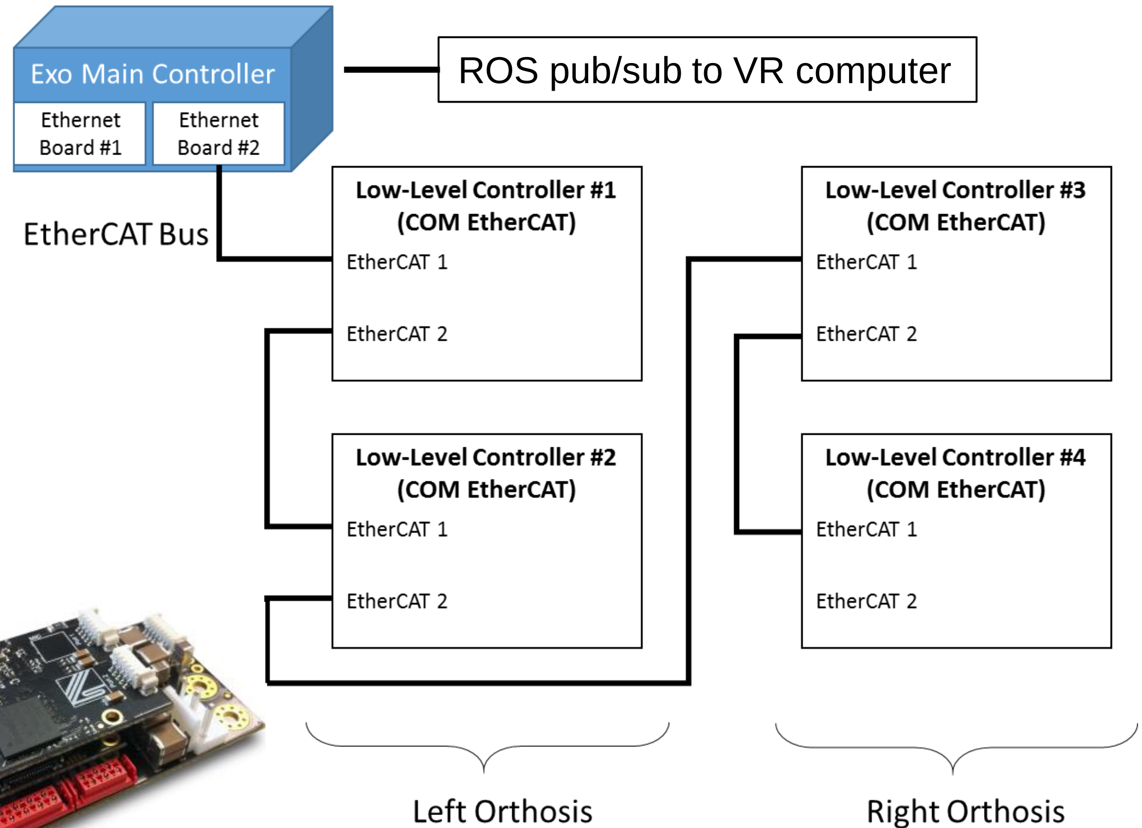
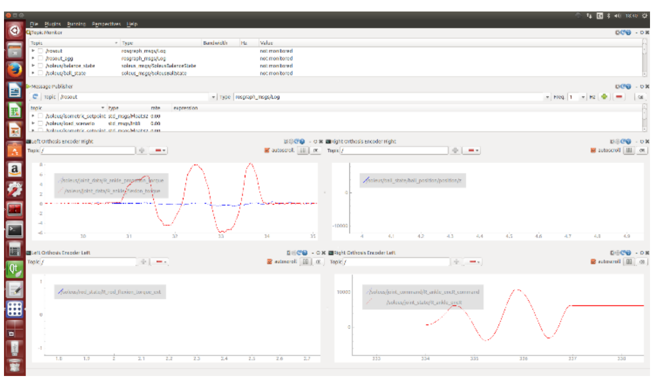


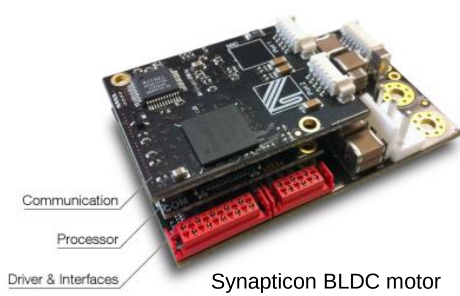


Lower Leg Exoskeleton

Mechatronics	
Ergonomics & Comfort	• Nylon straps • Foam Padding • COTS shin pad
Structure	• Thin Aluminium sheet • Alumide SLS 3D print • PA+GF SLS 3D print casing
Control & Electronics	• Integrated motor drivers • ROS based control • EtherCAT
VR	• Oculus rift HMD • Unity







Synapticon BLDC motor driver

Lower Leg Exoskeleton

Mechatronics	
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Structure	• Thin Aluminium sheet • Alumide SLS 3D print • PA+GF SLS 3D print casing
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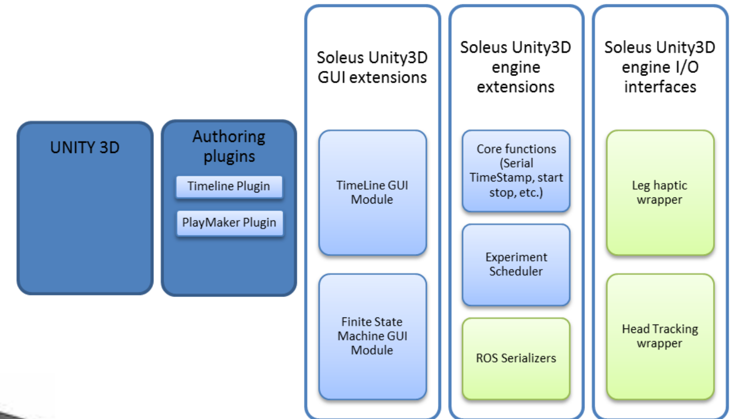
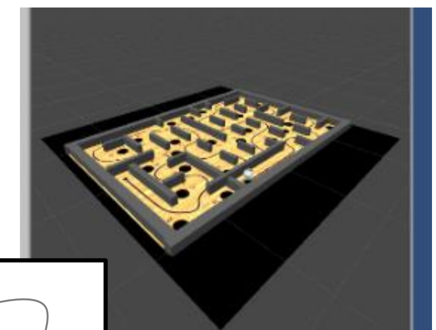
VR	• Oculus rift HMD • Unity

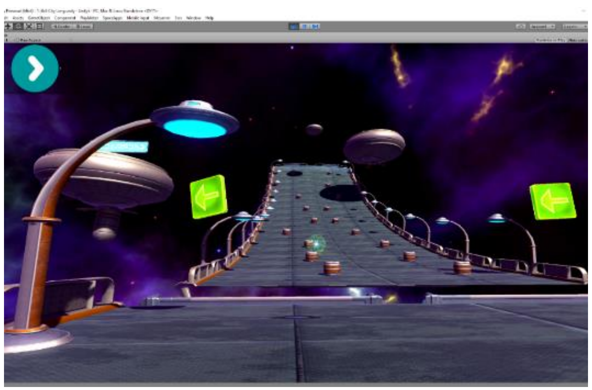
unity

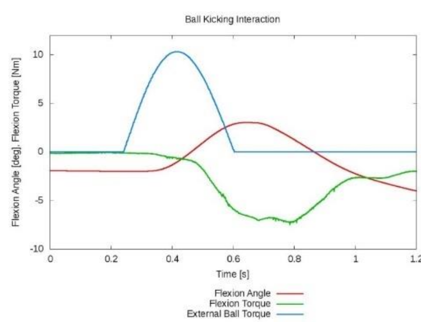
ROS

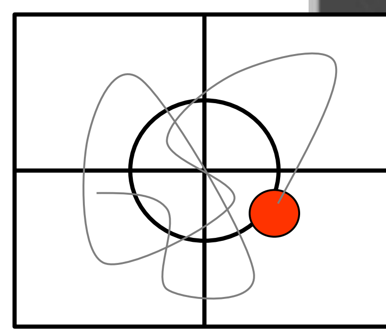
eVRS



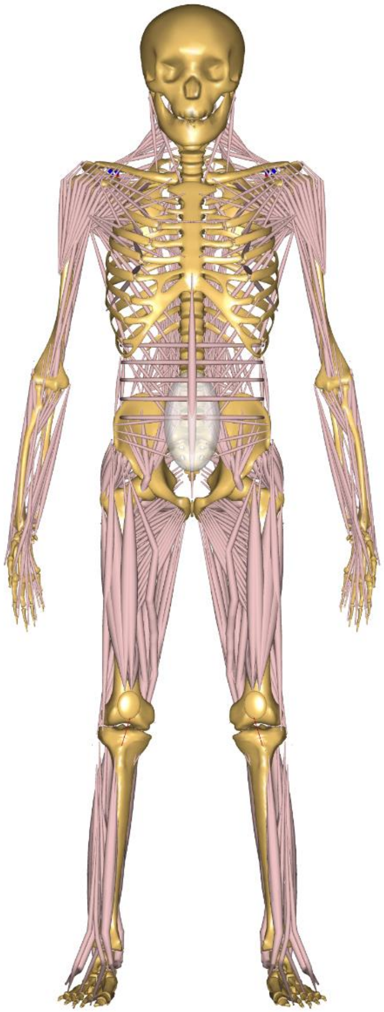








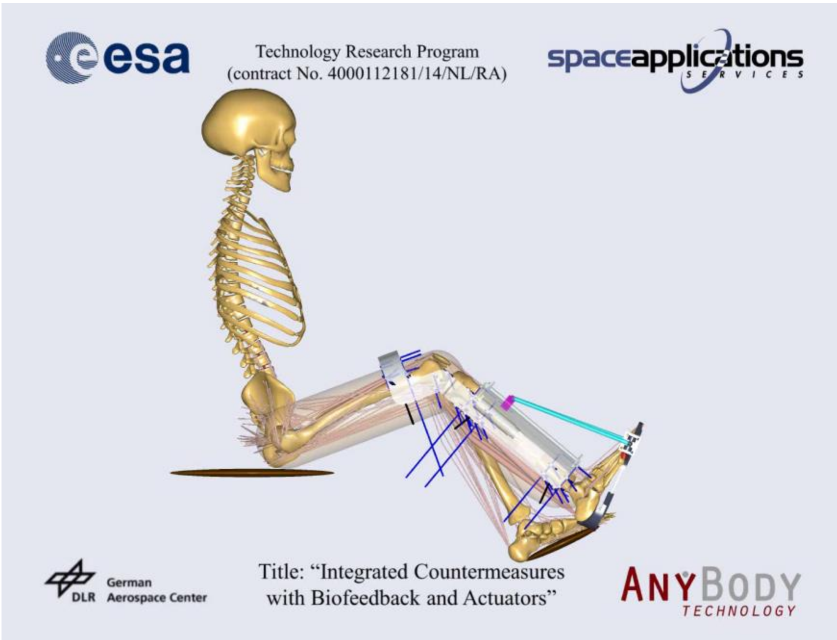
Musculoskeletal Simulation Using AnyBody Modeling System

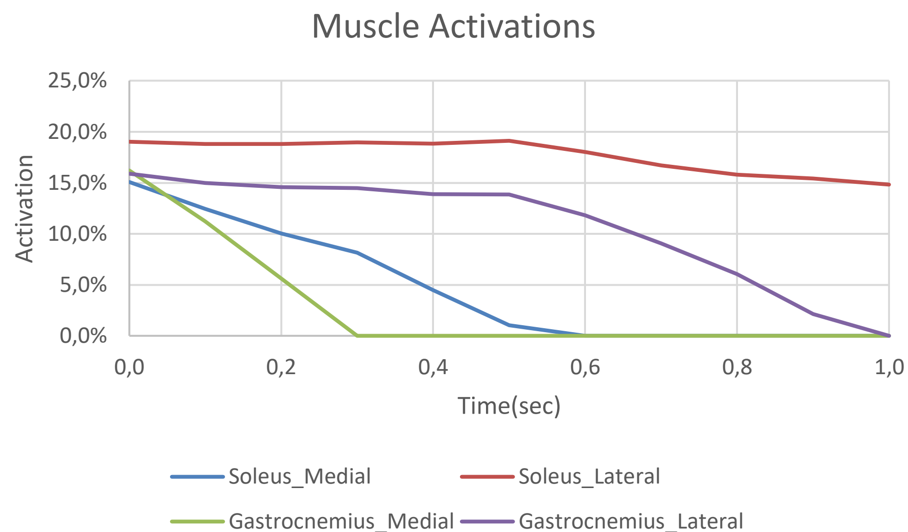


- Analysis of possible exercise protocols and comparison of effectiveness of the most promising concepts to support the final selection of design:
  - Muscle activations
  - Joint reaction forces and moments
  - Actuator profiles(loads and kinematics)
  - Interaction forces

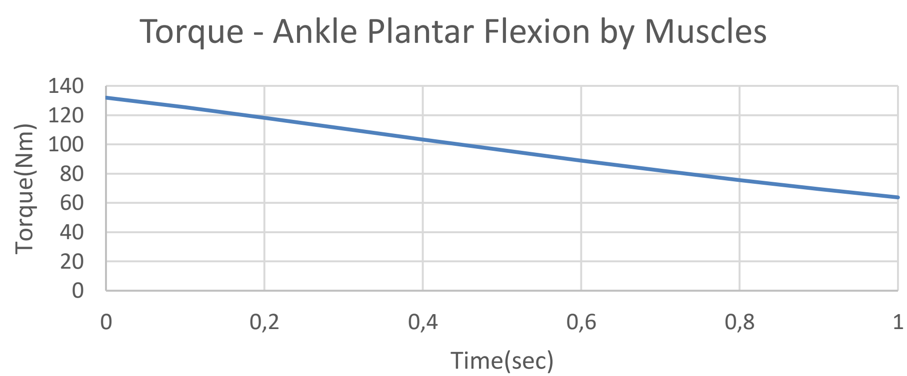
- Identification of the main parameters of the system defining the effectiveness of the selected concept, as support to the detailed design

Scenario: Pedal Pulling to the Foot



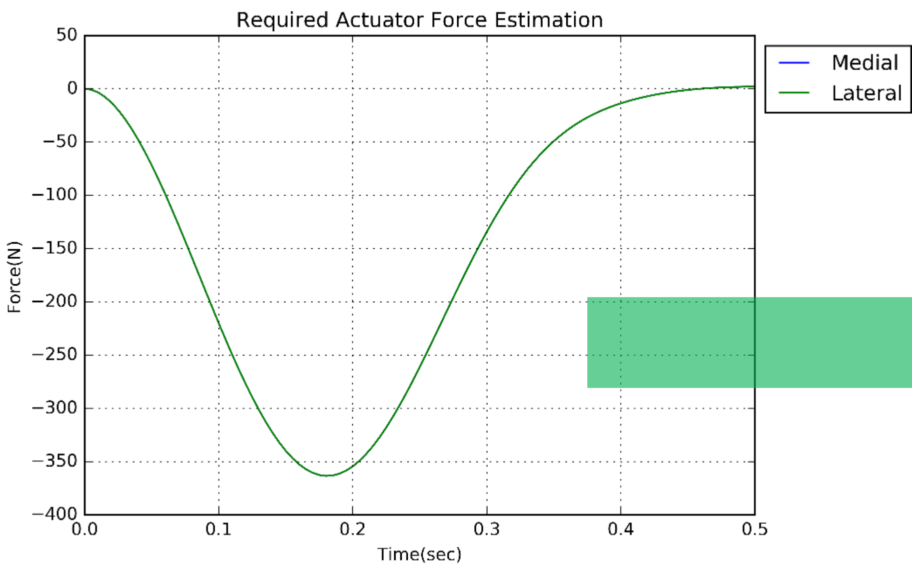


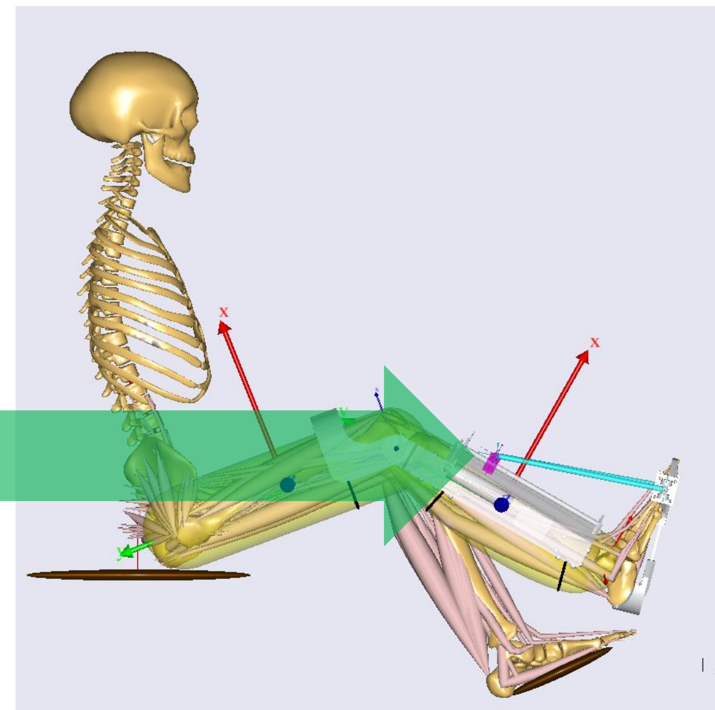
Parameters	Values
System	Linear parallel design
Dorsiflexion max angle [°]	20
Plantarflexion max angle [°]	40
Plantarflexion speed [°/sec]	60
Meidal actuator force [N]	-400
Lateral actuator force [N]	-400



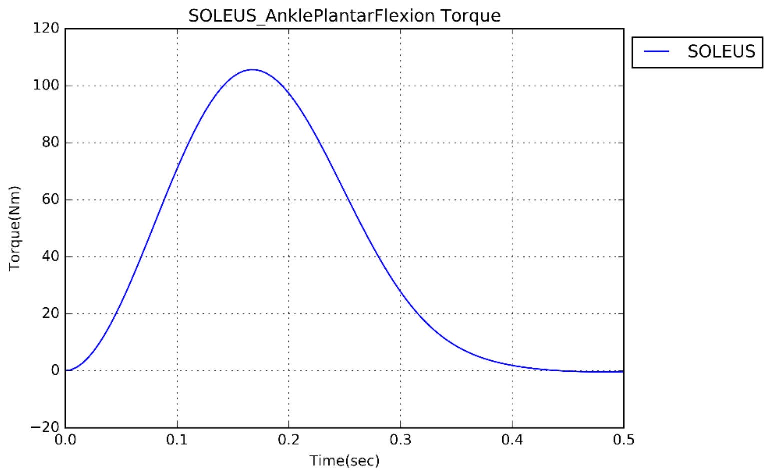
Scenario: Box kicking

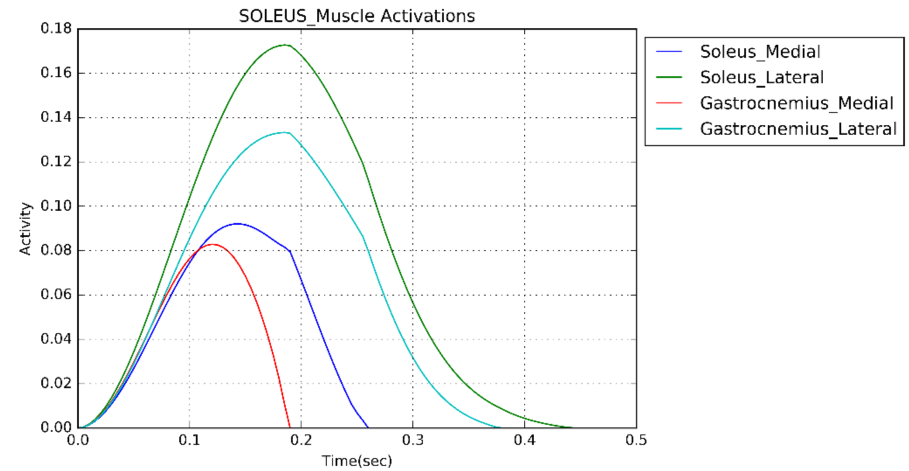
- Applying the actuator force profile which is supposed to generate the necessary amount of ankle plantarflexion torque by muscles
  - Inputs: linear actuator’s kinematics(position, speed) and kinetics(force)
  - Outputs: Ankle plantarflexion torque by muscles and muscle activations

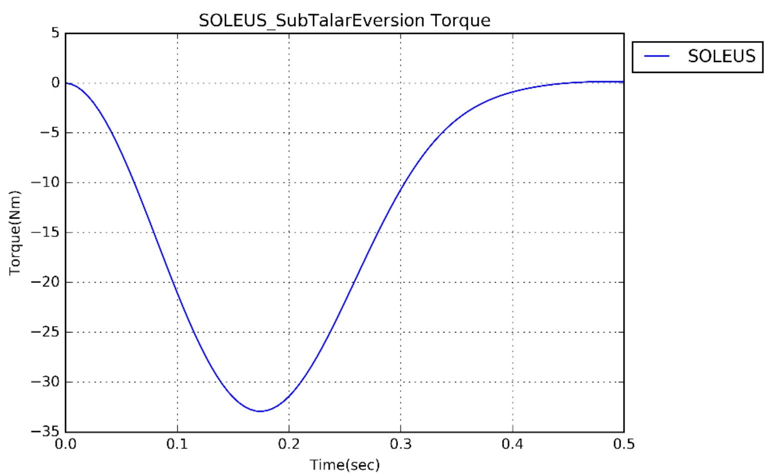


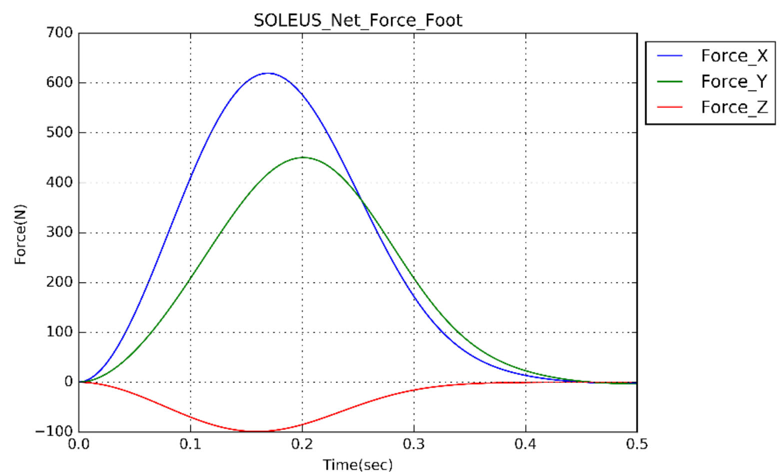


Scenario: Box kicking









Conclusions of using AnyBody Modeling System

- Purpose of musculoskeletal simulation
  - To test several possible exercise protocols of the system
  - To identify main design parameters of the system

- Useful outputs from musculoskeletal simulation for SOLEUS device
  - Ankle plantar flexion torque by muscles
  - Muscle activations
  - Interaction forces

- Some limitations of simulation compared to real experiments:
  - Only the comparison between simulated muscle activation and EMG is available
  - Simulation assumes a single subject whereas there are multiple subjects in the experiments
  - The assumptions of simulation are not as same as the conditions of the experiments

Conclusions of using AnyBody Modeling System

- Suggestions of using musculoskeletal simulation for possible future projects
  - Development of multiple subject scenarios in order to cover various range of populations in terms of mass, height and muscle strengths
  - Development of additional outputs from musculoskeletal simulation
    - Comfort index can be a useful measurement from simulation
    - Development of comfort index should be validated by user ratings from real experiments
  - Improvement of simulating interface forces between human and device
    - Strategy of modeling
    - Useful information from experiments during the development of simulations
  - Better alignment between the scenarios of simulation and experiments

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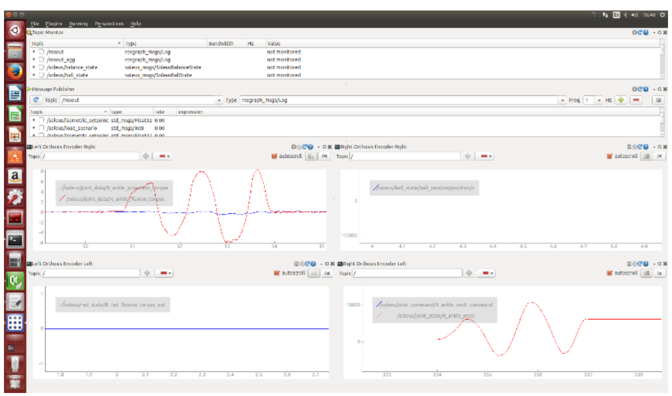
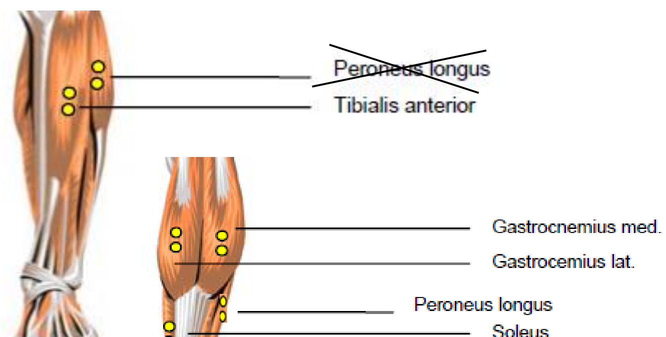
Scientific Evaluation Purpose

- Validate of the main functions of the system and bring evidence of the potential of exoskeletons as countermeasure devices
- Evaluate the potential benefit of the Virtual Reality stimuli in countermeasure applications (e.g. increased stimulation)
- Compare the Soleus system performance (including muscle activation) with standard scientific apparatus(e.g. Isomed 2000)
- Asses human factors such as ergonomics and comfort
- Analyse the effectiveness of the system (hardware, software) from subject and operator point of view.

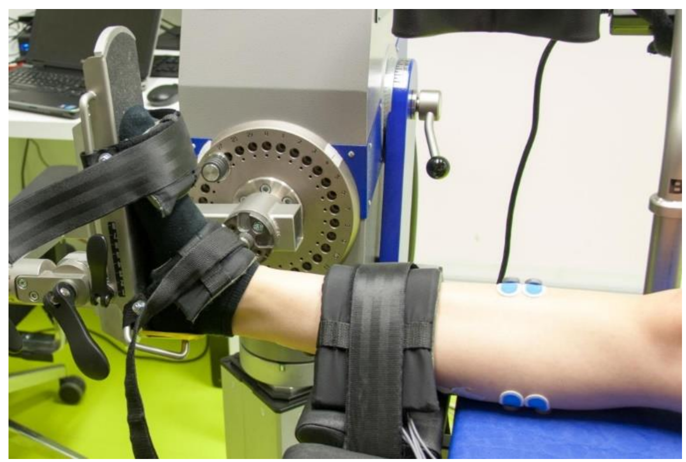


SOLEUS Operations: Study Set-up

- Study was conducted in the physiology lab of Envihab at DLR, Cologne
- Conducted on 15 subjects (8 female, 7 male)
- Reference tests on Isomed 2000
- Isomed was also used as carrying structure for the SOLEUS
- EMG data acquisition (5 positions)



EMG MyoSystem 1400A, 4 A/D channels



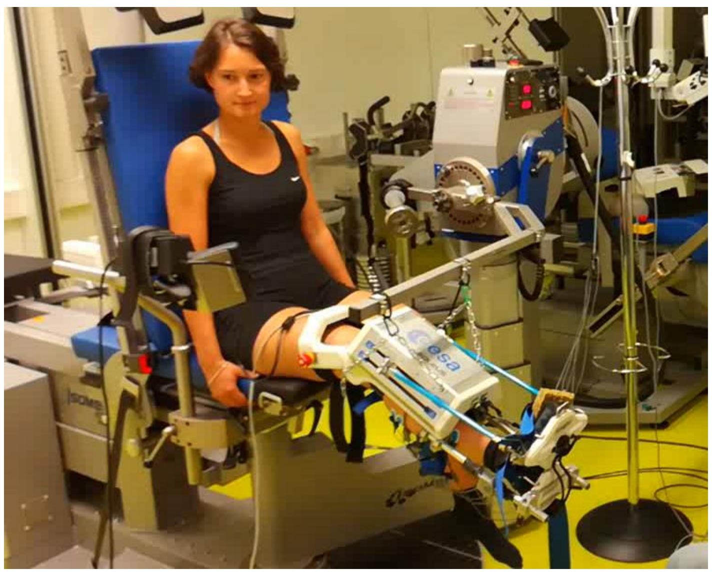
Standard Scenarios

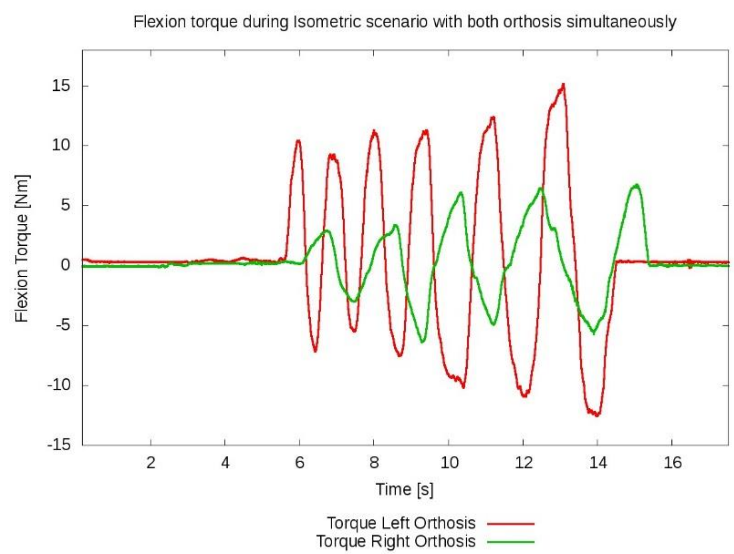
Isometric Maximum Voluntary Contraction (MVC) of plantar flexion and dorsi-flexion,

Neutral foot angle, 90° and 0° knee flexion, foot platform is locked.

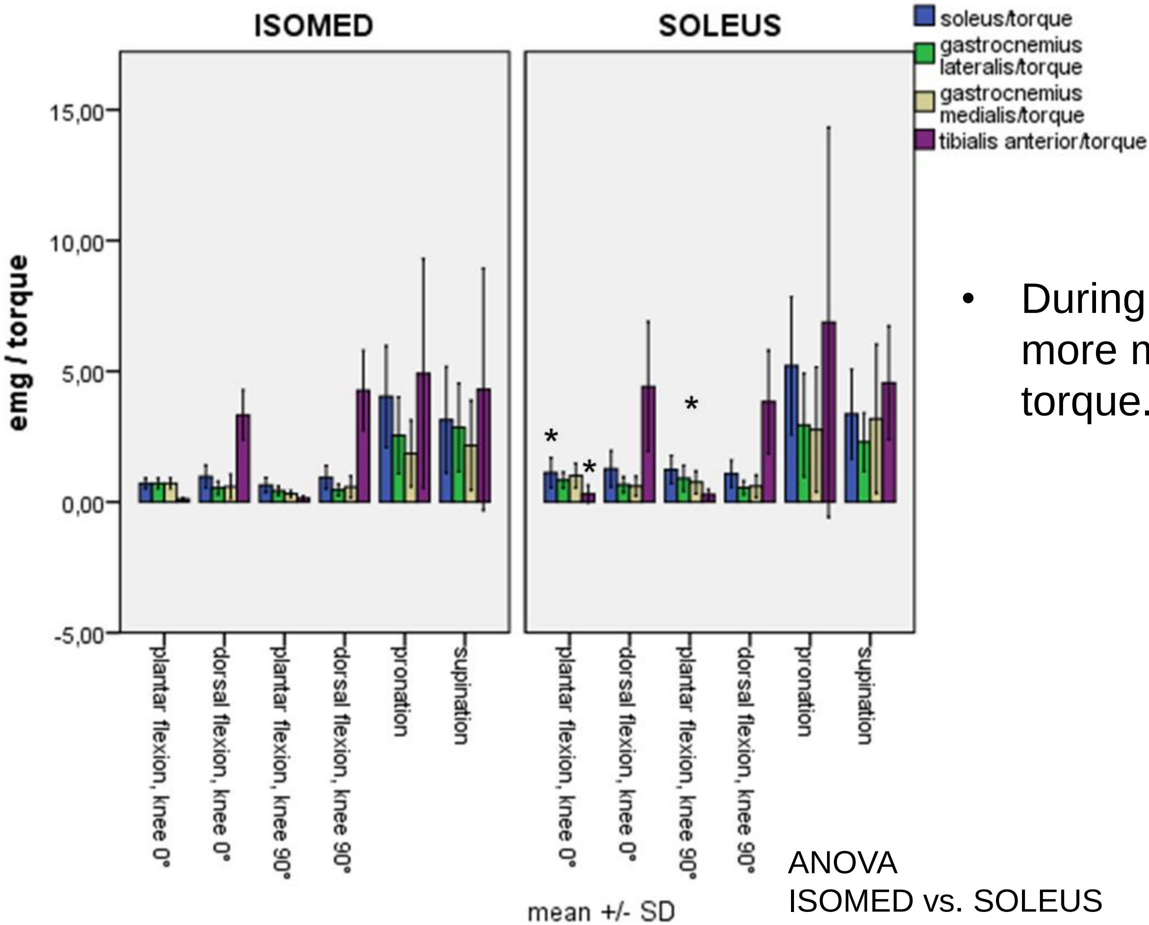
Aims:

- Comparison with values reached on a dynamometer dedicated for MVC testing (e.g. ISOMED 2000)
- Determination of maximum EMG amplitudes for the normalization of EMG amplitudes in further test





Isometric Contraction: Normalized EMG / Torque



- During plantar flexion on the SOLEUS-device more motor units (MU) were activated for a give torque. (On SOLEUS, torque was controlled)

ANOVA
ISOMED vs. SOLEUS
* p<0.05
** p<0.01

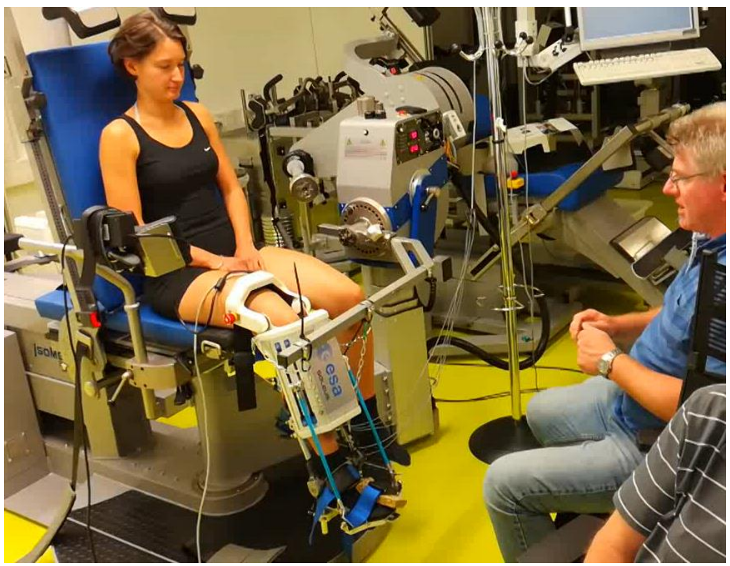
Standard Scenarios

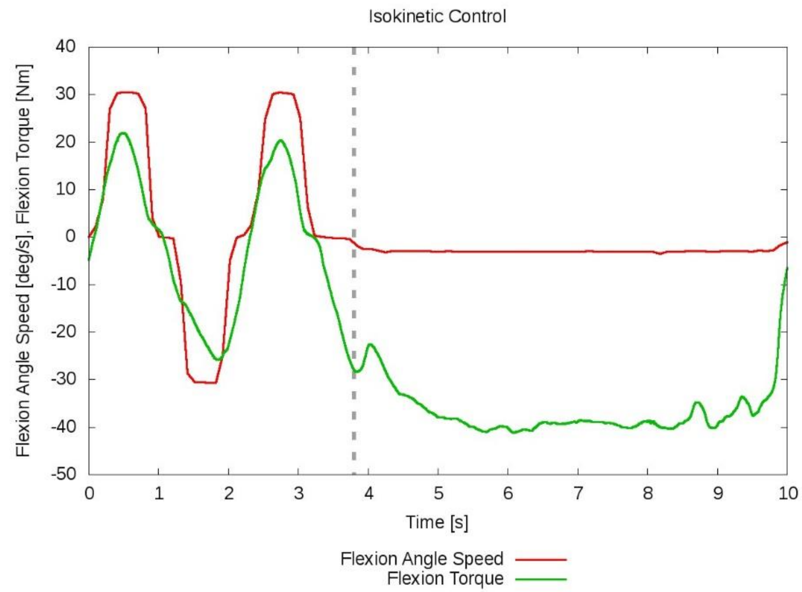
Isokinetic exercises

Knee flexion 90° and 0°. The foot platform is only movable in plantar flexion /dorsi-flexion plane

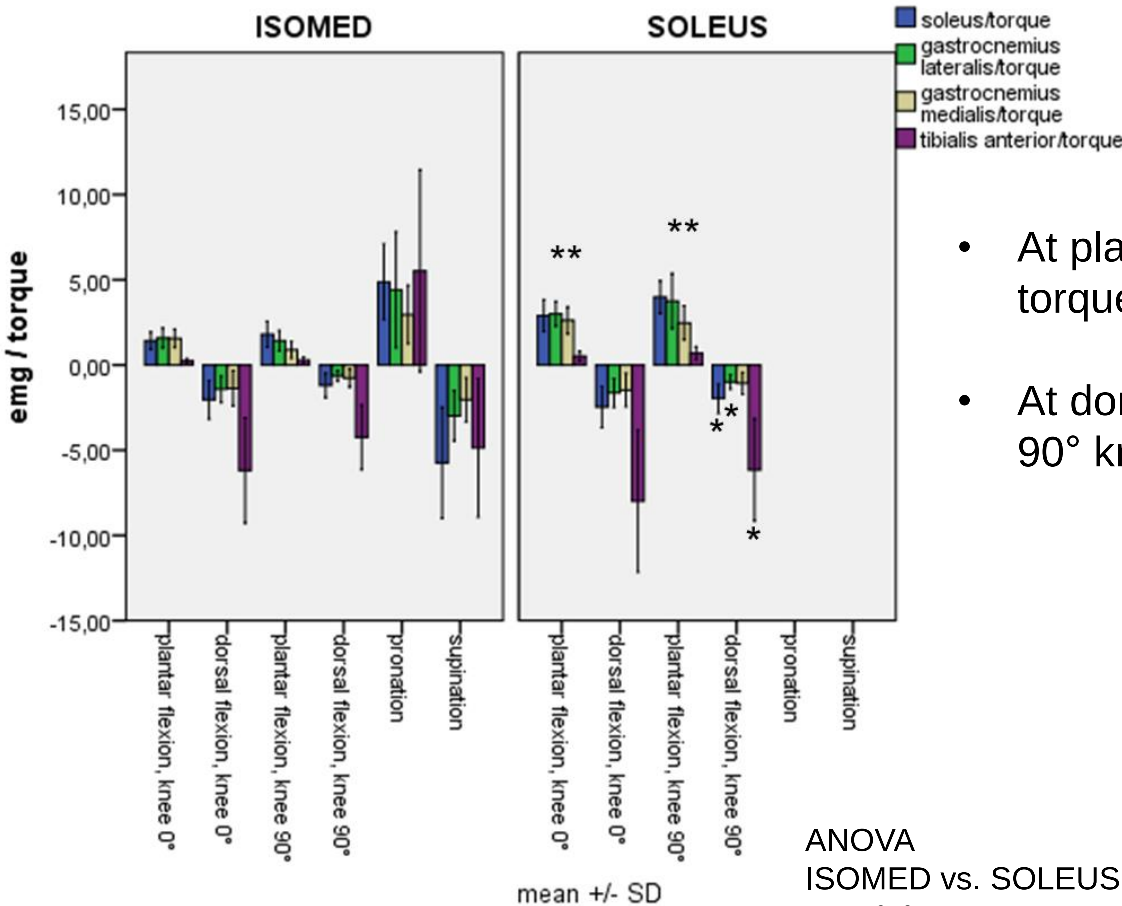
Aims:

- Comparison with values reached on a dynamometer dedicated for MVC testing (e.g ISOMED 2000)
- Fit and ergonomics of the SOLEUS device under motion
- Motor unit activity (EMG)





Isokinetic Contraction: Normalized EMG / Torque



- At plantar flexion in SOLEUS, EMG amplitudes per torque were higher for of all muscles.
- At dorsal flexion this effect was only significant at 90° knee angle.

ANOVA
ISOMED vs. SOLEUS
* p<0.05
** p<0.01

Isometric - Isokinetic Conclusions

- When subjects were allowed to perform maximum voluntary contraction, torque levels and the patterns of muscle activation were similar between the two devices.
- In the SOLEUS device, isometric and isokinetic plantar flexion at reduced torque levels resulted in higher EMG amplitudes/torque in comparison with the MVC performed on the ISOMED. (Different tasks: controlling a force level vs. contracting as much as possible)
- On SOLEUS isokinetic contraction was performed with too much caution. Likely higher torques at lower EMG/torque could be possible.
- For comparisons between ISOMED and SOLEUS torque values of up to 300 Nm should be reached by a future SOLEUS to allow maximum isometric plantar flexion.
- In addition contractions with controlled submaximal torques should be compared on both devices as well.

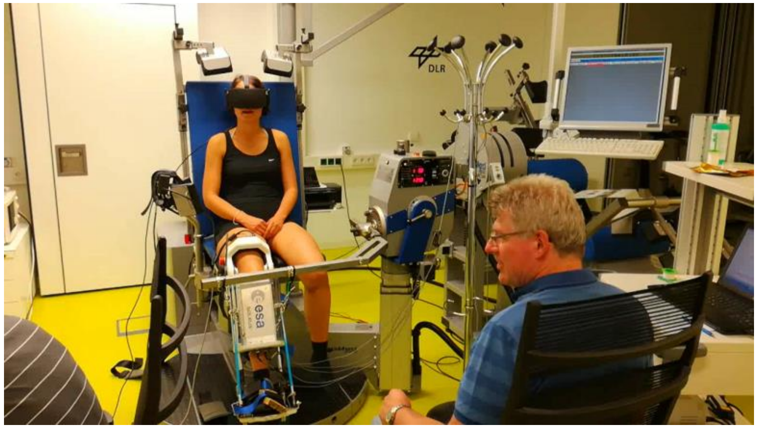
User Scenarios, Serious Gaming and VR

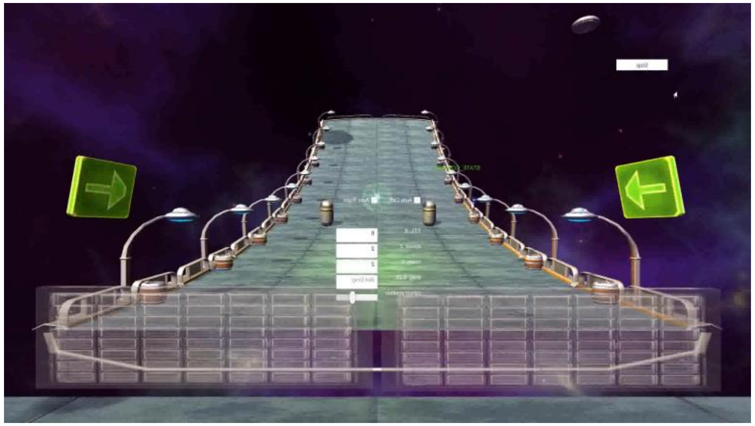
The “Ball-kicking” exercise

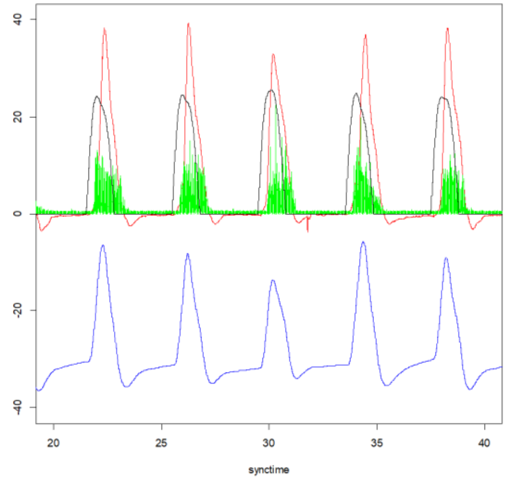
Moving object (MO, “box”) is kicked with both feet, flies and lands back on the feet like a ballistic body under Earth gravity. The MO is kick immediately away.

Specific aim:

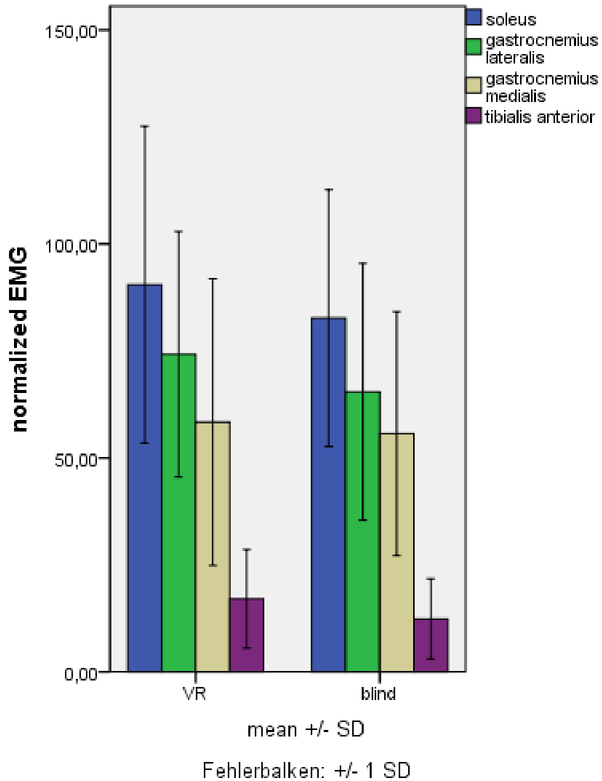
- Investigate new approach of countermeasure exercises
- Compare muscle activation with other testing scenarios
- Stressing the elastic and damping properties of the calf musculature and the Achilles tendon.

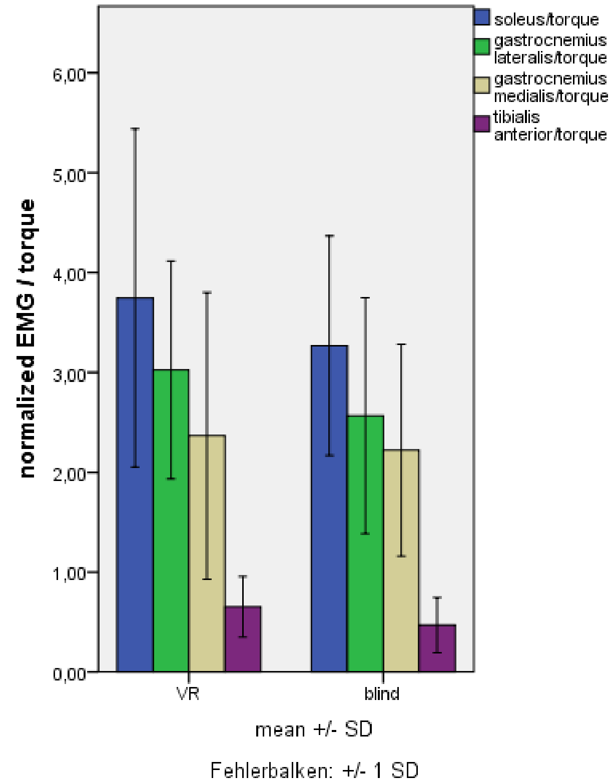






Ball-Kicking EMGs





- Muscle activation was very similar with the isokinetic plantar flexion.
- Soleus muscle almost reached the activation level of 100% isometric MVC.
- Effect of VR not significantly proven

Ball-Kicking Conclusion

- The ball-kicking scenario allowed to stimulate strongly the lower-leg muscles group reaching almost 100% activation isometric MVC
- With the current set of parameters for the orthosis control and the ball interactions, the behaviour is similar to isokinetic plantar flexion.
- There is a large set of parameters (orthosis control and dynamics, ball/pedal interactions) that can be investigated to change the interaction of the system. That could trigger different type of user's reactions
- The influence of the VR can not be significantly proven with the current set of experiments, although we showed that is it possible to combine it with the mechanical stimulation.

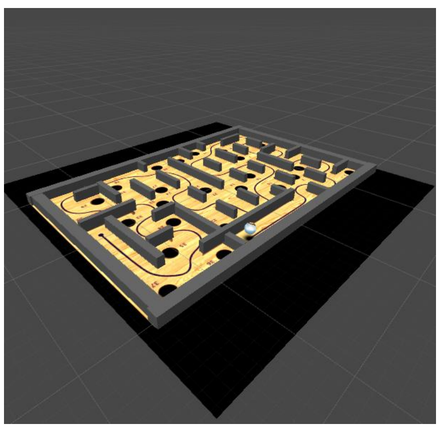
→ Possible causes or investigations:
  - Reduced number of tests and large variations of people reactions in this more complex scenario
  - Improvement of the physical interaction model (parameters and algorithms)
  - Improvement of the realism and synchronization of the VR rendering (bending of objects)
  - Simplification of the VR for higher focus on the task
  - Improvement of the felt orthosis dynamics by the subject (remaining friction and inertia)

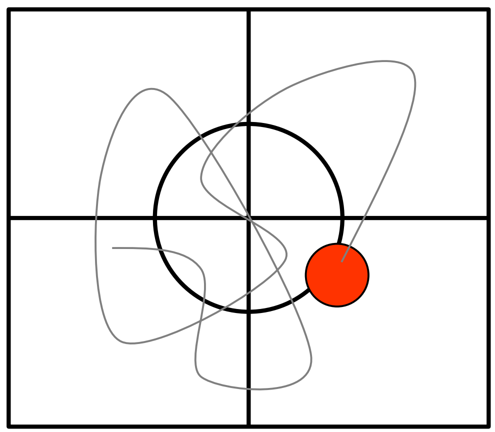
User Scenarios, Serious Gaming and VR

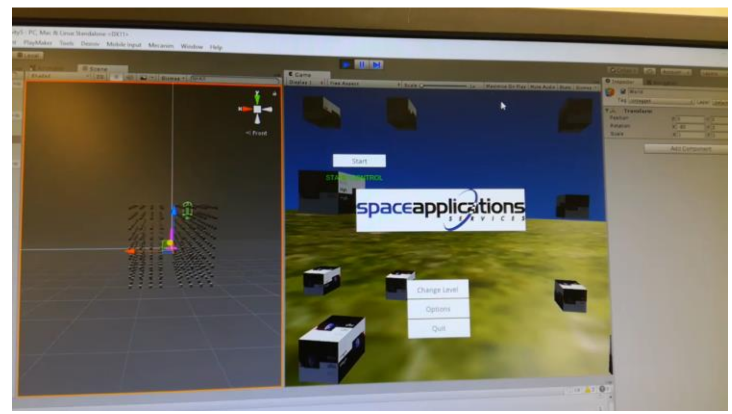
2DOF Ankle Balance control

- Virtual reality scenario with unstable platform that can be controlled by the foot to guide a ball in a maze game
- Control of the ankle orientation under random perturbation
- Stimulation of neurological pathway reflex under unbalanced visual triggering (external to the scientific evaluation)

Specific aim: Improving motor control, performance on ankle stabilizing muscles and vestibular feedback.

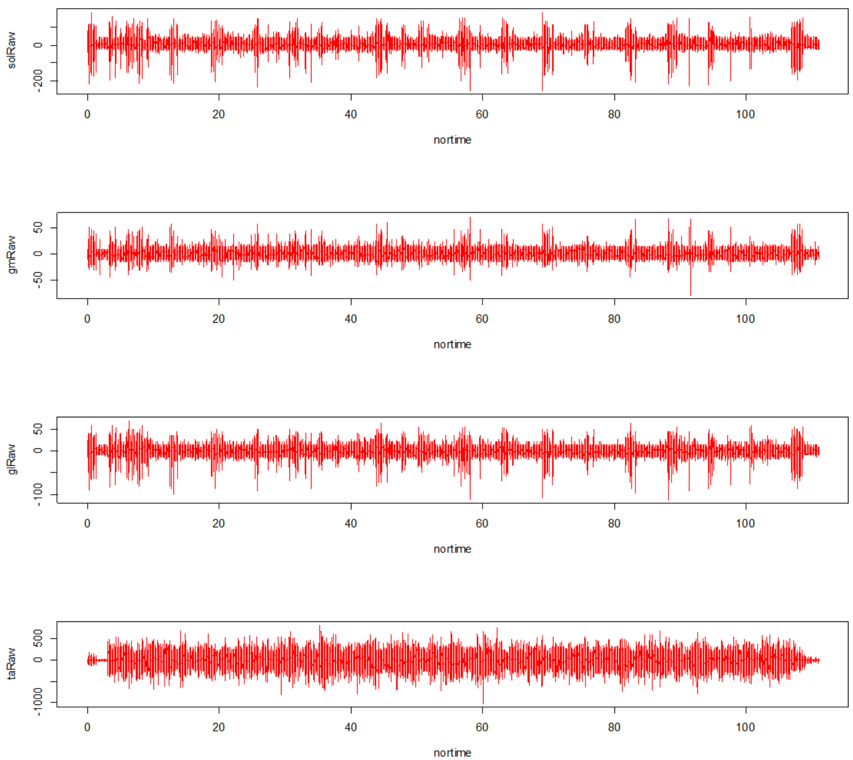


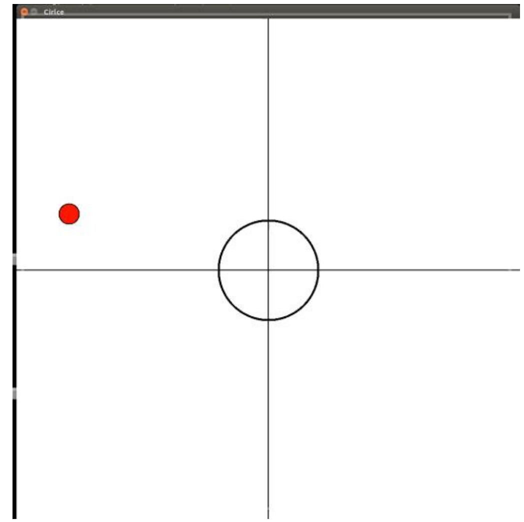




2 DoF Balancing Stimulation

- Keeping the red point inside the circle against disturbing external torques





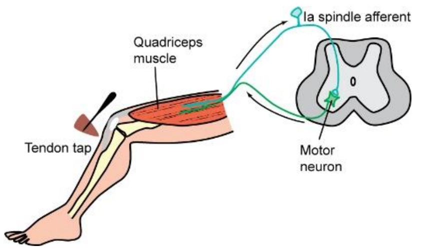
2 DoF Balancing Conclusion

- With the 2 degrees of freedom version, a simulation of a balancing scenario is possible.
- SOLEUS device can produce and resist sufficient levels of torque for a balancing scenario.
- With an intuitive visualization (here a point that must be kept inside a ring) the subjects are able to react on externally disturbing torques with increasing ankle joint stiffness and controlled counter movements.
- Highest priority must be given to the synchronization between VR and SOLEUS.
- Improve physical models that simulate more realistic situations

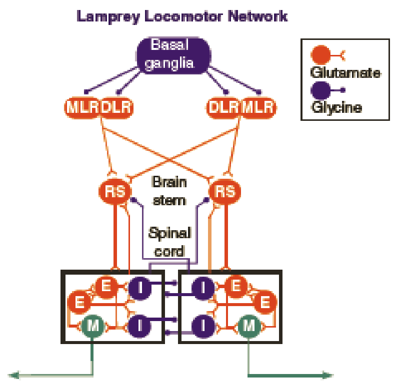
Neural Pathways of the Motor System

Spinal Circuits

reflexes and central pattern generators



(*a*)



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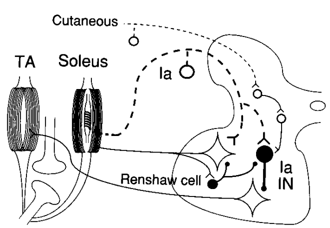
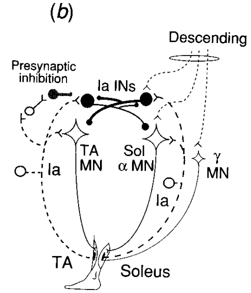
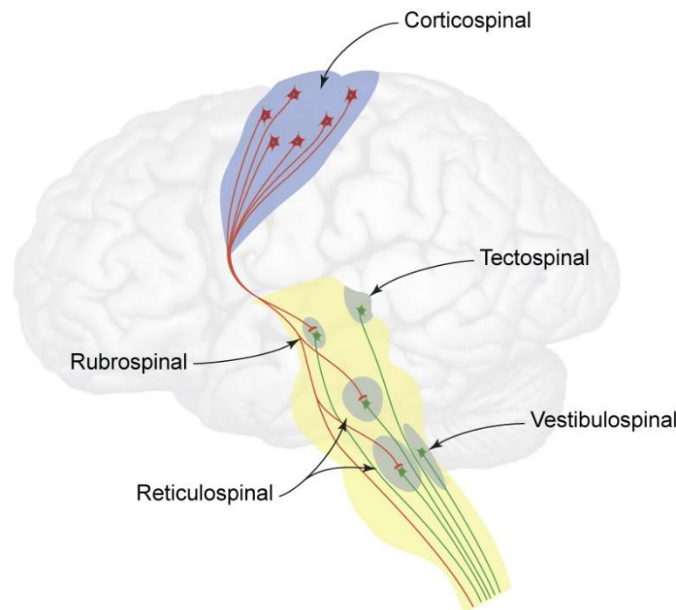




Descending Commands

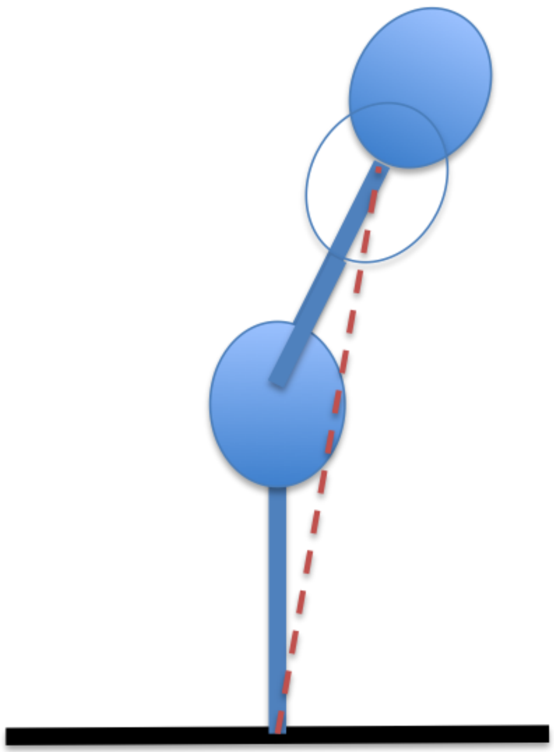
posture, voluntary movement



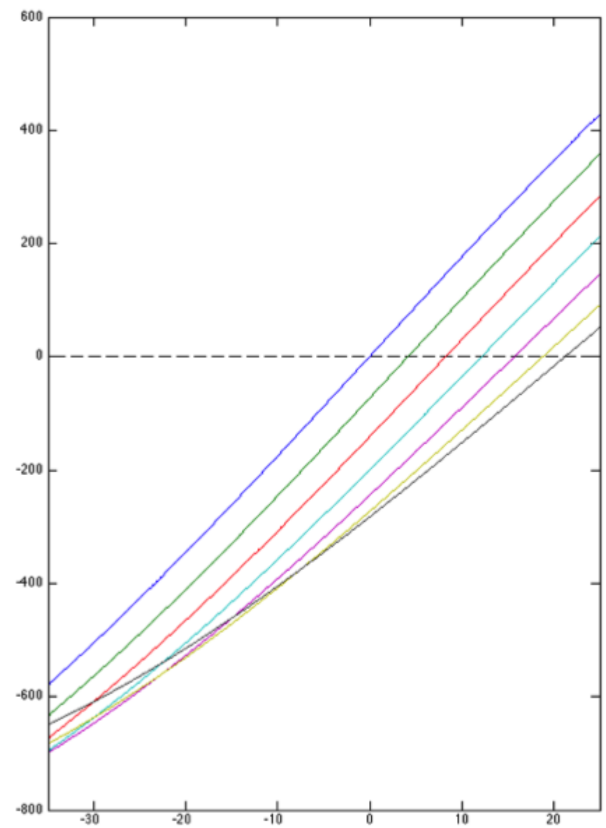
Implications for SOLEUS

- **Hypothesis**:
  - Exercise will be more efficient for combating loss of muscle mass if muscles are activated by each of the different possible neural pathways.
- **Rationale**:
  - The distribution of muscle motor units is not necessarily uniform across the different sub-systems. By involving the different subsystems one can reach a greater percentage of the motor units and muscle fibres.
  - It's not all about muscle mass. Immobilisation, bed rest and weightlessness decreases the ability to activate muscles.
  - Need to maintain sensorimotor function as well as muscle mass.
- **Implications**:
  - Devise protocols using the SOLEUS exoskeleton and eVRS virtual reality to exercise the postural, locomotor, reflex and voluntary movement subsystems

Upright posture is characterized by mechanical instability at the ankle.

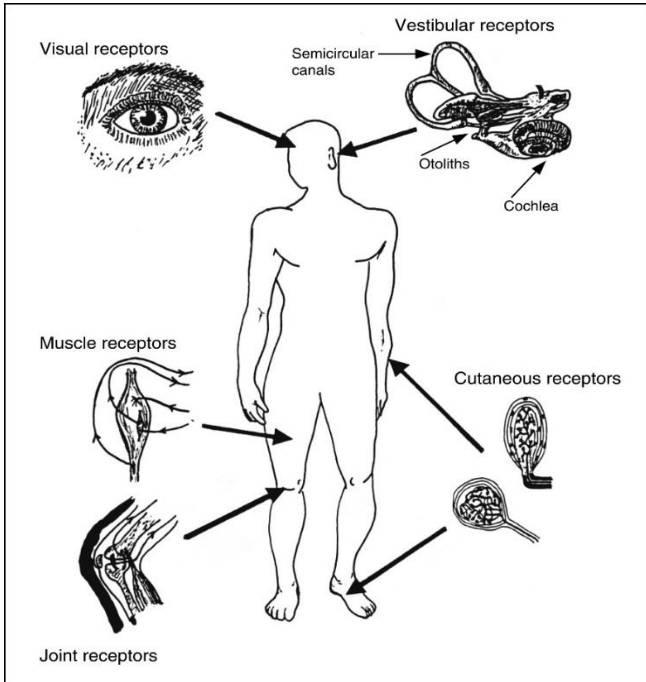


mechanical model



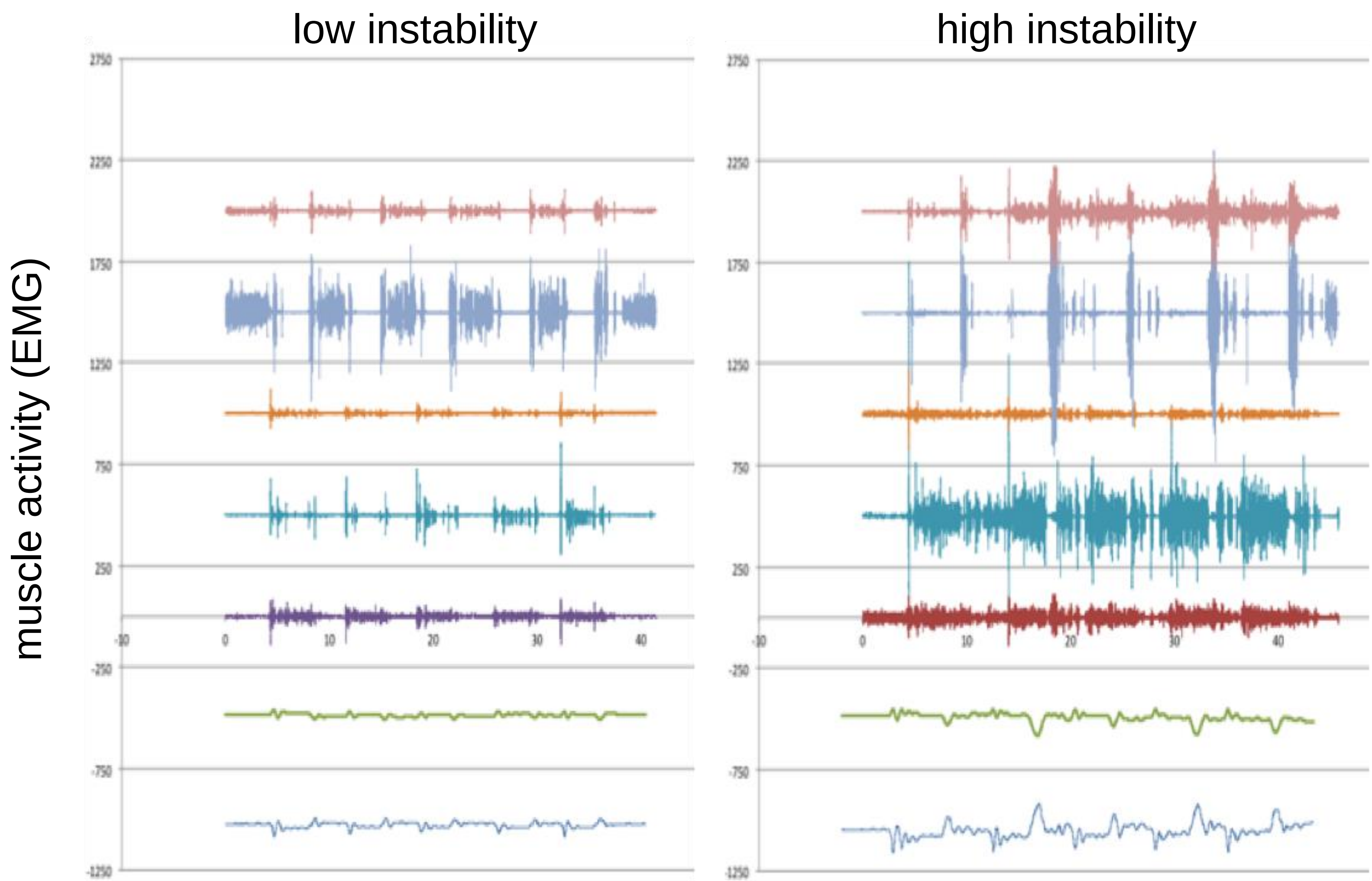
ankle angle

Posture is a Multi-Sensory Activity.

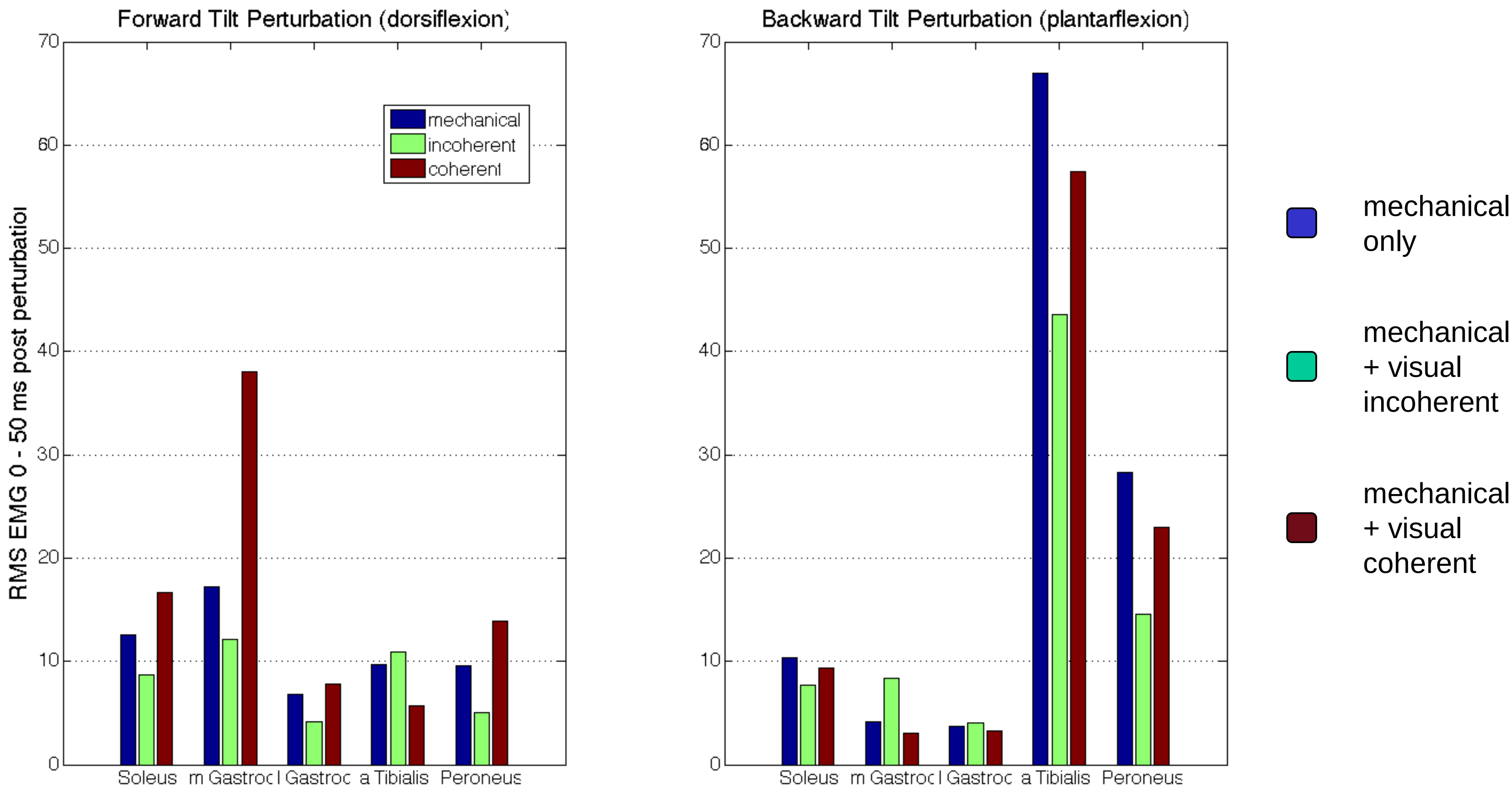


- Simulate a postural task with visual and mechanical perturbations.

Effect of Ankle Instability (negative stiffness)



EMG Response to Mechanical + Visual Stimulation



- Interaction between visual and vestibular perturbations.

Conclusions

- Hypotheses
  - Stimulate muscle responses by diverse neuronal pathways
    - May recruit additional muscle fibers
    - May serve to maintain 1g reflexes (e.g. postural reflexes)
- Results
  - Clear effect of postural instability on EMG levels
  - Clear interaction between visual and mechanical perturbations
- Proposed Improvements
  - synchronization of signals
  - command from VR to orthosis
  - multi-joint orthosis
- Perspectives
  - Fully test the hypothesis concerning recruitment of motor units
    - single unit recordings
  - Test balance simulation in absence of conflicting graviceptor cues
    - parabolic flight
  - A wealth of studies to be performed to explore visuo-vestibulo-kinesthetic interactions
- Can I have one?

Agenda & Outline

- General Introduction and Motivations
- Part 1 - Scientific and Technical Background
- Part 2 - Concepts, Detailed Design and Integration
- Part 3 - Scientific Evaluation
- Part 4 - Recommendations and Perspectives
- Open Discussion

Review of the Orthosis Concept

Kinematics and Actuation Drive Concept

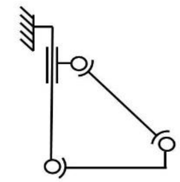
Advantages:

- Double DoF with ankle natural motion
- High level of torque
- Compactness + integration
- Isolated from external influence

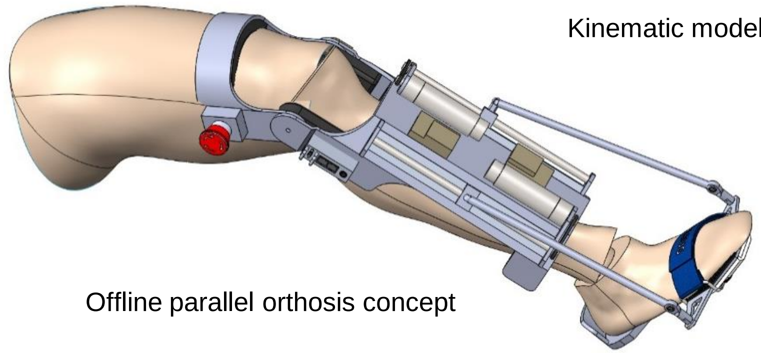
- Back drivability with low reduction gear
- Open access to ankle
- Compatibility with upper leg design extension
- Compatibility with space hardware requirements

Complications:

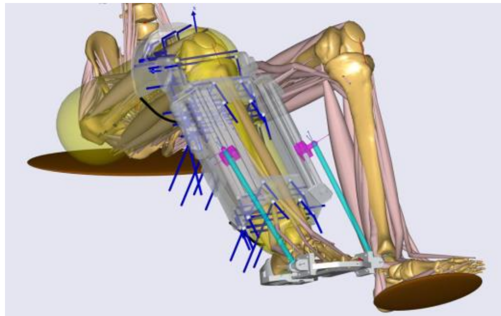
- Range dependency to user size changes
- Advanced kinematics
- Linear motor size limitations



Kinematic model concept



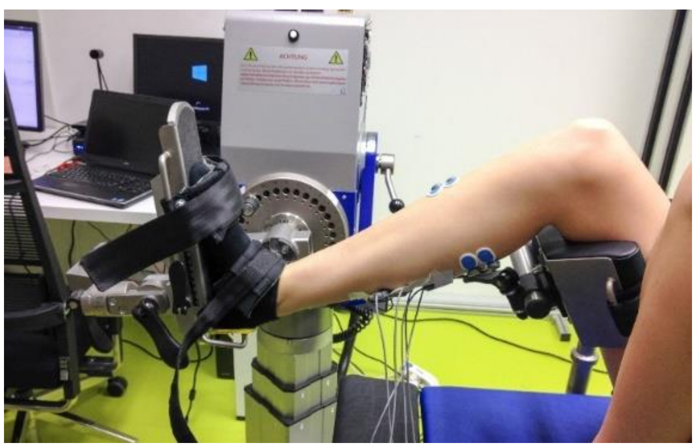
Offline parallel orthosis concept



ABT simulation of the SOLEUS orthosis

Review of Orthosis Comfort and Ergonomics

- Design of the concept and of the final orthosis has taken into account user comfort, user range, ergonomics, fixation methods… extracted from the WP1 state of the art study.
- But the WP6 scientific tests have shown new behaviors of the subjects regarding fully isolated exoskeleton countermeasure devices with closed loop mechanical interactions:
  - The foot straps were generating pain, limiting system functionality but the calf were not affected by the fixations.
  - The human body adapts fast to ergonomics constrains (e.g. joint not aligned).
  - For very demanding exercises (multi DoFs or high loads), the subjects use the maximum potential of exoskeleton even by applying unforeseen directions of loads.



Fixation of the upper leg and foot during WP6

EMG + strap effect on skin after long exercises

Recommendations on Comfort and Ergonomics of a Lower Leg Countermeasure Exoskeleton

1. Maintain natural motion and flexibility to human kinematics
   Controlling the flexibility and adaptability of the human limbs without disrupting the realism of the exercise is the most important part of the exoskeleton design.

2. Comfort of the attachments points to the human body
   A device that is not fully transparent for the user in term of comfort will lower drastically the outcome of the countermeasure objectives

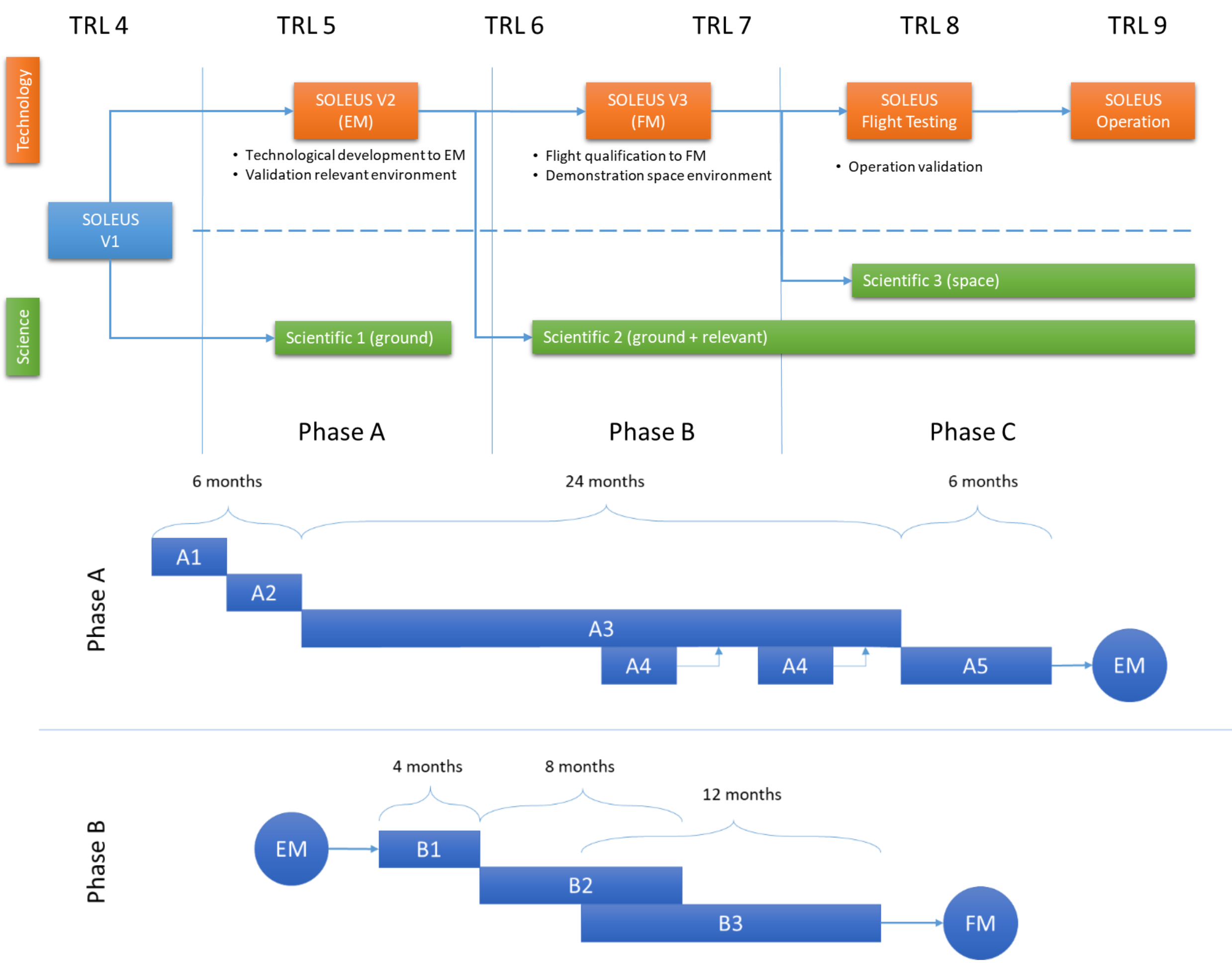
3. User size adjustments and safety range stops
   The orthosis must be flexible and compatible with variations of size and shape without impacting the efficiency and comfort of the device.

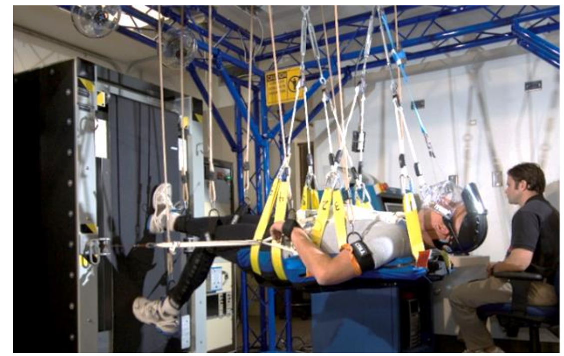
A good control of the human limbs during the full exercises without disturbing the realism of the motion is the core of the development of a countermeasure exoskeleton. The rest of the mechatronics work can be extracted from engineering work and designs.

Recommendations on Exoskeleton and VR Interactions

- Recommendation to include visual stimulation either in 2D or 3D immersive virtual technologies in future countermeasure applications:
  - Entertainment and stimulation (e.g. competition)
  - More options for training tailoring
  - Opportunity to investigate new training approaches (e.g. neuro-vestibular stimulation)
  - Can be associated with exoskeleton technologies but also in large scope of applications.
- Hardware Technologies involve very quickly, as well as supporting software tools, but can still be time consuming to understand and deploy good applications
- Improve and ensure consistency between VR visual rendering and force rendering to improve user experience and avoid bad side effects (e.g. one integrated simulation).
- Evaluate the need of real-time measurements and feedback, especially for sub-millisecond synchronization during scientific experimentation.

SOLEUS Flight Model Roadmap





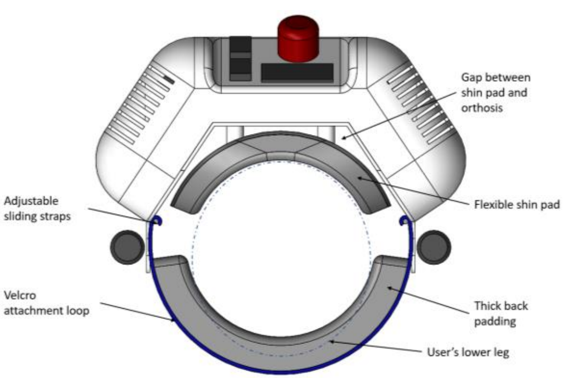
A1: Scenarios and requirements consolidation
A2: Concept Consolidation
A3: Detailed Design, MAIT
A4: Test 1 (BSS)
A5: Final Testing (Parabolic Flight)

B1: Update design
B2: MAIT FM + Training
B3: Qualification Process

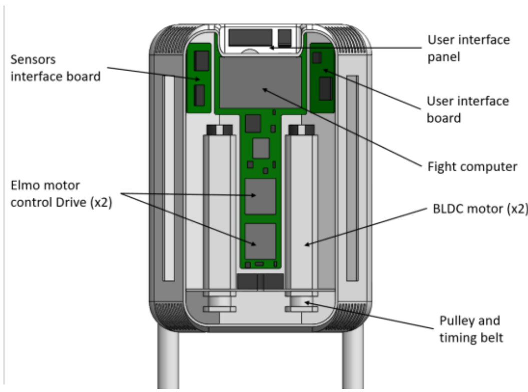
SOLEUS Flight Model Concept

Update from ground prototype to flight model concept:

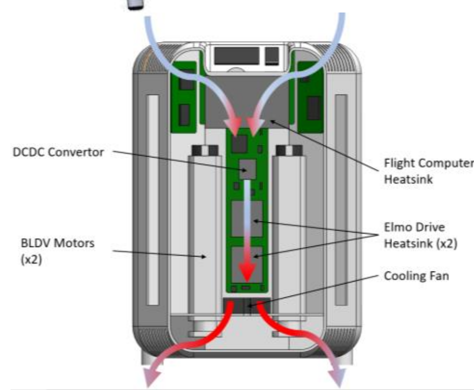
- Same kinematics as SOLEUS
- Knee joint removed
- Range limitation sensor + STO
- Simplified foot segment
- Heat management
- Imbedded electronics
- Single front plastic casing



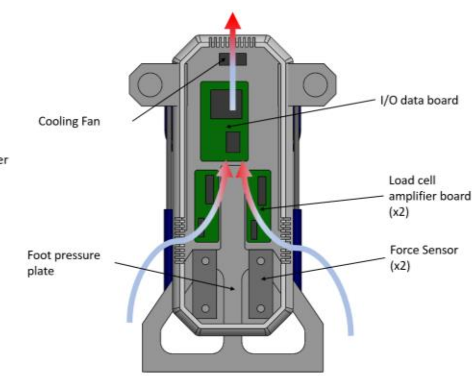
Orthosis comfort straps + back padding



Orthosis imbedded electronics



Orthosis heat management



Foot heat management

SOLEUS Applications and Perspectives

- Applications:
  - Space Countermeasure / Measuring system
  - Ground Rehabilitation (post flight / clinical) and physiotherapy (2DOF, natural ankle motion, use at home)
  - Scientific test bench, medical research (e.g. neuroscience experiments)

- Perspectives:
  - Synergies with future multi-purpose exoskeleton developments (e.g. Athletics, FITS like training device)
  - Integration/adaption to multi-DoF leg exoskeletons:
    - Increase number of muscles solicited
    - More realistic, functional VR scenarios to simulate balance, walking, running
    - Improved multi-joint coordination
  - Scientific follow-up interest with the current device
  - Clinical validation investigation

Project Conclusions

- The SOLEUS project succeeded to develop an innovative product combining exoskeletons and VR technologies, targeting space countermeasure applications.
- The system has been validated during a Scientific Evaluation and provided interesting conclusions in order to justify follow-up experimentation and developments.
- Experiments and tests have highlighted the main difficulties of design, especially regarding comfort and user interfaces (including VR consistency) that would require high attention in future projects.
- Potential for space and ground applications with upgrade to full leg devices.
- In order to reach a flight model, it would require improvement of usability, compactness but in contradiction with requirements of torque/velocity capabilities.
- Importance to provide to development teams, precise scenarios and training requirements to better target the development.

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