ATHLETIC: Pseudo Anthropometric Exoskeleton with a Semi Passive Actuation System for Countermeasure

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ABSTRACT

This paper presents the ongoing ESA project ATHLETIC ('AstronauT HeaLtH EnhancemenT Integrated Countermeasure') which aims to develop a new approach of integrated countermeasure device in the shape of an exoskeleton. It focuses primarily on the training of the lower limbs, which are the most heavily affected body parts while astronauts are exposed to microgravity. The ATHLETIC system enables High Intense Resistive Training exercises (HIRT), as well as plyometric exercises such as hopping and jumping. Development and validation shall give an answer to the question if exoskeleton technology is suitable for countermeasure in zero gravity and how such a system performs compared to existing countermeasure devices for zero gravity applications.

1. INTRODUCTION

During spaceflight, the human body is exposed to a microgravity environment, which results in various physiological adaptations. Some effects, like vestibular disorders, lead to temporary discomfort for some days. Other processes like bone mineral loss or muscle atrophy affect the physical condition of astronauts in proportion to the time spent in space [5]. 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).

As shown by [1], the main effects of deconditioning related to bone loss and muscle atrophy occur in the lower part of the body. This is mainly due to a nearly permanent absence of mechanical loading and neuronal activation when living in microgravity environment.

For long duration missions to space, fitness procedures and programs are required to counter the effects of living in microgravity. Ideally these measures retain Earth-bound baselines. These actions and related devices can be collectively termed countermeasures. Effective countermeasures are necessary for astronauts to successfully react to emergency situations, to remain functional in space and to ensure minimal post-flight rehabilitation upon their return to Earth.

Current training devices used on board the ISS like the Treadmill with Vibration Isolation System (TVIS) or the Advanced Resistive Strength Training Device (ARED) are only partially able to conserve the function and mass of lower body musculature. Hence, to enable adequate exercises to contain strength and bone density of astronauts, new approaches for countermeasure devices must be considered.

2. PROJECT OBJECTIVES

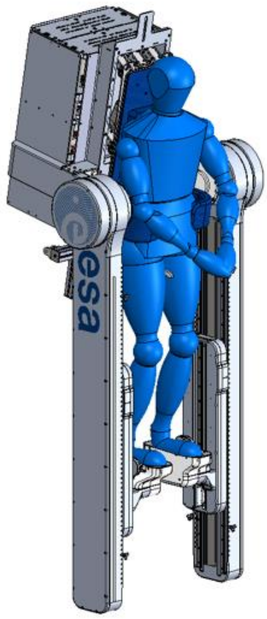


Figure 1. Computer rendering of the ATHLETIC exoskeleton with user.

The project ATHLETIC aims to develop a novel countermeasure device combining a pseudo-anthropometric exoskeleton structure (see Fig. 1) with semi-passive actuation, targeting high resistance loads exercises and simulated short term ground reaction forces (impact loading like jumping and hopping) to allow plyometric exercises both dedicated to conserve strength and mass of the musculature and bone density in hips, upper legs, and lower legs [6].

2.1. ATHLETIC DEVICE – KEY FEATURES

Prominent characteristic of the ATHLETIC device are its pseudo anthropometric kinematic in form of two linear rails which are positioned on the side of the user's legs. Using linear rails to transfer loads to the user's feet is beneficial when dealing with high forces in the kinematic chain. A purely anthropometric kinematic based on rotary joints only has to withstand high torsion load especially when the legs of the user are retracted. This is not the case with the presented pseudo anthropometric kinematic solution based on linear motion. An additional advantage of this approach is that the maximum load can be generated independently of how long the user's leg is or how much their legs are stretched or retracted. The approach is also beneficial for comfort, no braces or any other thigh fitting connections between the legs of the user and the exoskeleton are needed. This negates a persistent problem with lower body exoskeletons: the systems must be securely attached to the legs however the circumference of the calf and thigh changes throughout the motion as different muscles contract. This causes abrasions and pain. The linear rail approach does away with these, only hip and foot restraints are needed. This design also simplifies user-specific setup. No adjustment of the exoskeleton legs is required to adapt to users of different heights. This obviously reduces the setup time and the ease of use of the system. Finally, since the load applied to the user's feet is concentric to the user's centre of gravity (user COG) in all situations the risk resulting from loads which cannot be adequately compensated by the user is reduced. Subsequently this effect of the linear motion solution can be seen to increase the safety of the system to the user.

Second prominent characteristic is the drive concept. As depicted in Fig. 2 two novel, semi passive actuation systems are used which allows to simulate g-load (constant Force) and inertia loads independently. This unique drive solution supports the following benefits:

- Drastically reduced energy consumption.
- Reduced heat dissipation.
- More explosive exercises are possible compared to traditional active actuators solutions.
- Inherently increased system safety due to the fact that unexpected motions originating from drive malfunctions cannot happen with the proposed scheme.

The kinematic approach as well as the design of the single drive systems will be explained later in this paper.

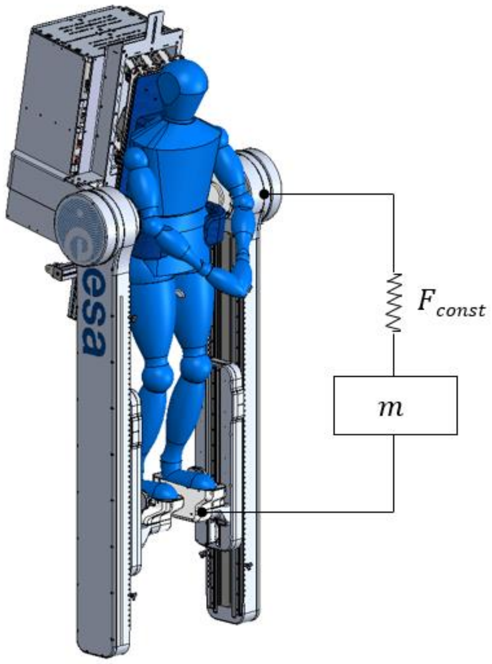


Figure 2. ATHLETIC exoskeleton with actuation characteristics.

2.2. HIGH INTENSE RESISTIVE TRAINING

HIRT essentially represents slow and safe strength training for activating muscle growth. For the lower body, examples of HIRT are squats, heel raises or leg press training (see Fig. 3). Loads are normalized on the subject's body weight at $1g$ or on a previously determined one repetition maximum (1RM). HIRT typically uses loads around 150% of body weight or 80% of 1RM that can only be moved in sets of about 10 repetitions.

Figure 3. Leg press exercise

2.3. PLYOMETRIC EXERCISES

Plyometric exercises exert short impacts in terms of rapidly increasing forces. When the muscle-tendon units (MTU) release their elastically stored energy and the musculature contributes active force short peaks of maximum force are typically reached. The goal of this type of training is to increase muscle power, muscle and tendon elasticity and the strength and elasticity of the corresponding bones. For the lower body this type of exercise mostly consists of jumping exercises such as squat jumps (see Fig. 4), hopping or power skips.

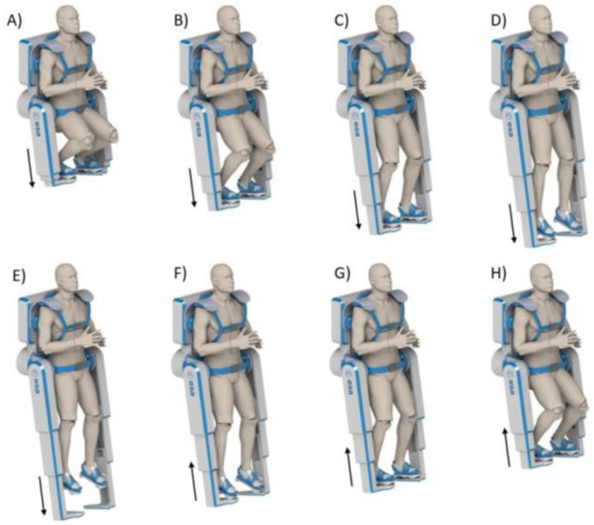


Figure 4. Squat jump sequence.

Tuck jumps or jumping lunges, require more coordination and are quite challenging in simulation as well. During plyometric exercise forces are naturally applied to the body by subject's weight and by velocity changes and mass inertia.

3. SYSTEM DESIGN

The ATHLETIC device is composed of two main elements which are the BackPack and two telescopic legs (see Fig. 5).

The BackPack is equipped with an upper body harness for user attachment. In addition, the BackPack contains the constant force drive modules as well as the avionics. The telescopic legs supports all kinematic elements to guide and load the user legs. The telescopic legs are equipped with sensors to determine linear and rotary joint positions as well as to detect the ground reaction forces. Additionally, the drive modules to simulate inertia loads are embedded into the telescopic legs as well.

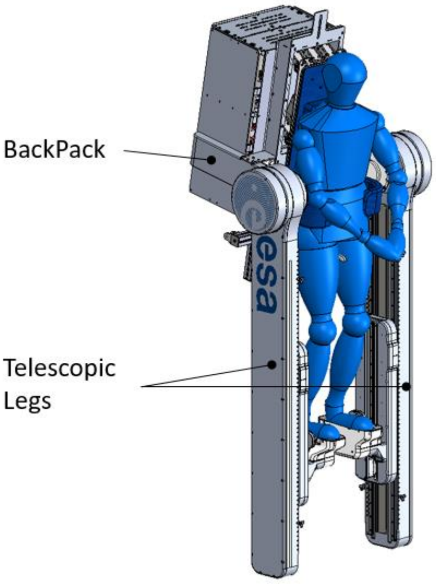


Figure 5. ATHELTIC exoskeleton with highlighted main structural elements.

A user terminal (not shown in Fig. 5) allows the user to interact with a graphical user interface (GUI) and to setup the device to perform the various exercises.

3.1. TELESCOPIC LEG DESIGN

As highlighted in Fig. 6 the telescopic legs are composed of the following functional units:

- BTA-Joint (**B**ackPack-**T**elescopic-**L**eg-**A**xis)
- Telescopic-Element-1
- Telescopic-Element-2
- Ground Plate
- Flight Guide

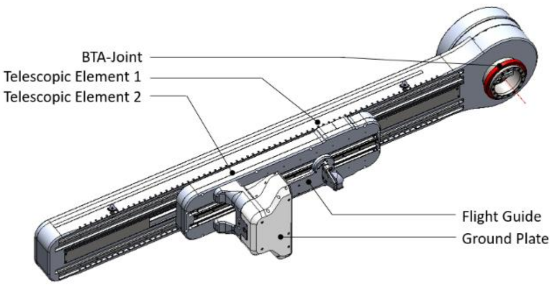


Figure 6. Telescopic leg sub-assemblies.

The BTA-Joint connects the telescopic rails with the BackPack. This joint is located such that it points towards the user's COG. In addition, the volume of the BTA-Joint contains the inertia module.

Telescopic-Element-1 contains main linear rails as well as adjustable end-stop features for safety aspects to be able to define the working range of the linear motion as required for each user and/or exercise.

Telescopic-Element-2 can move linearly along Telescopic-Element-1. It supports the Ground Plate which finally transfers ground reaction forces to the user's feet. Embedded in Telescopic-Element-2 is a second linear rail to guide the Flight Guide unit. This part guides and constrains the motion of the user's feet in the event of a jump. This feature ensures that the user always lands on the Ground Plate and by that safely can perform jumping exercises.

The Telescopic Rails are dimensioned for P1 to P99 user size. Furthermore the length of the rails allows a jumping height of up to 60cm. Fig. 7 shows the positions of the telescopic legs as well as the user's leg (P50 user size) in the collapsed, extended and jumping situation.

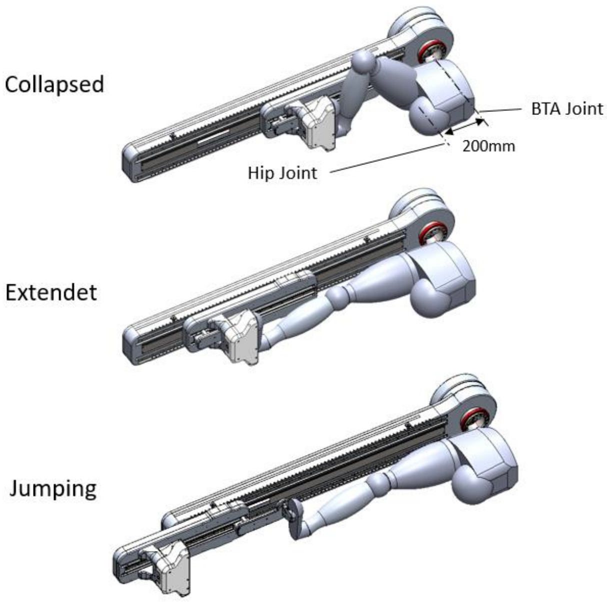


Figure 7. Three positions of a telescopic leg.

As can be seen the offset of the user's hip joint to the BTA joint is estimated at 200mm but can be fine adjusted by the adjustment means integrated in the BackPack.

3.2. CONSTANT FORCE MODULE

The constant force mechanism is an independent element of the full drive system which acts in parallel to the inertial part. The mechanism is duplicated in the backpack with one unit for each linear rail. A rendering of the mechanism itself is shown in Fig. 8.

The mechanism can buffer potential energy in a set of mechanical coil springs. To change the linear behaviour of the springs from deformation-dependant force to a constant force a mechanism introduced by Herder [2, 4] is applied and adapted to compensating internal loads. A force adjustment motor drives a lead screw which can move a set of pulleys which allows to increase or reduce the generated constant force from zero to its maximum possible value. The lead screw has a self-locking effect which locks it in place without requiring additional electrical power. Hence, only when a change of the constant force is required, electric power is needed which leads to the definition of a semi-passive drive solution.

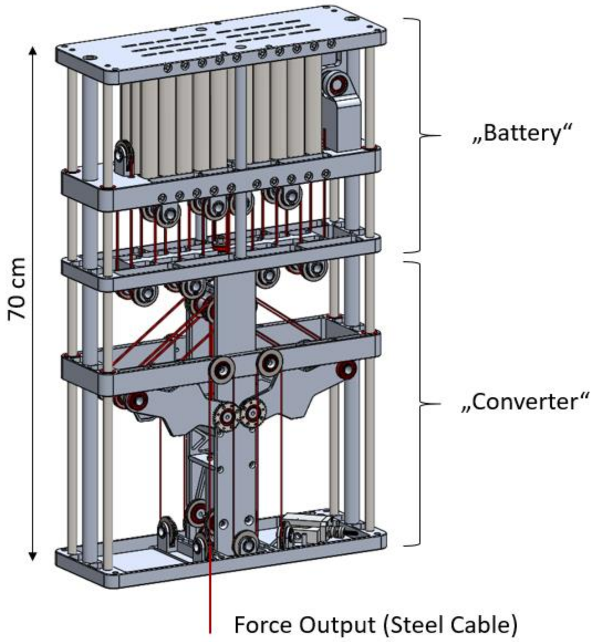


Figure 8. Constant force module

Fig. 9 shows an isolated test of a single constant force module, offloading a mass of 20kg. When integrated into the ATHLETIC exoskeleton each constant force mechanism is able to simulate buffer up to 900J. The cable transmission system that transfers the constant force output form each constant force module to the telescopic legs is designed that a maximum constant force of up to 280kg can be generated to press on the users feet.

The combination of small moving masses and low speed of those compared to the speed of the constant force output leads to negligible inertial effects of this mechanism. This in particular allows for high speed motion accelerations and velocities such as expected during jumping motions. In addition the feature of not adding inertia load to the telescopic legs by the constant force mechanism allows for adjustment of the required inertia by the inertia module exclusively.

Figure 9. Constant force module testing.

3.3. INERTIA MODULE

Unlike what happens when hopping and jumping on the ground, the user's body is not intended to accelerate when performing exercises with the ATHLETIC exoskeleton. Hence, the impulse when touching the "virtual" ground must be simulated by the exoskeleton. This is the task of two rotary masses that spin at high speed. The high speeds reduce the mass required to achieve the desired inertial effects. The applied inertial system is shown in Fig. 10. By using two masses that rotate in opposite directions, radial forces transferred to the support structure are compensated.

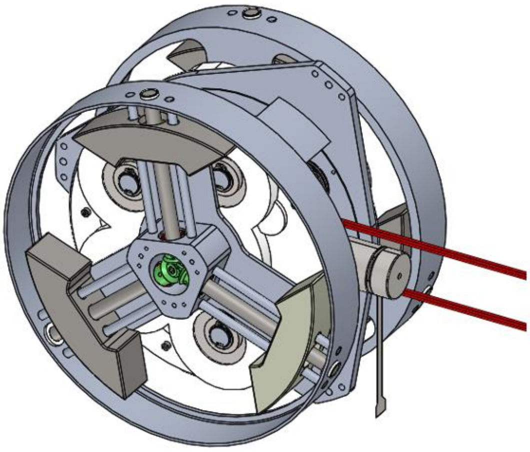
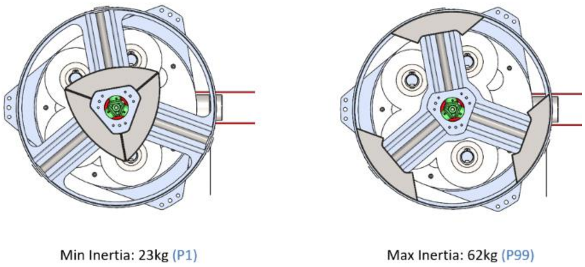


Figure 10. Inertia module.

As shown in Fig. 10 the rotating masses are mounted on a wheel structure by lead screws. The lead screws are driven by a central bevel gear on each wheel. These bevel gears are connected by a differential gear which is connected in turn to an adjustment motor. The motor itself is statically connected to the support structure.

The motor is used to move the masses inwards or outwards to decrease or increase the simulated inertia (see Fig. 11). This design avoids having motors mounted inside the rotating wheels and the associated signal and power transfer issues.



Min Inertia: 23kg (P1)

Max Inertia: 62kg (P99)

Figure 11. Inertia module – Min/Max inertial configurations.

The inertial forces are transferred by a pulley system to the linear rail. Fig. 12 shows the inertia module placed at the BTA-joint inside the telescopic legs (close view in Fig. 13). The cables are guided through a set of pulleys which are positioned in a radial manner inside the inertia module and transfer the rotation inertia into a linear acting inertia at the Telescopic-Element-2.

Figure 12. Inertia module – Change of inertia.

Whilst the system may look similar to a yo-yo at first glance it is quite different. A yoyo has a string wrapped around an axle which is unspooled as it goes down. When the spool is empty the yoyo brutally inverts its direction of rotation and generates a strong impulsive force. Because of the amount of energy released in a short period of time such events are hard for the user to counteract and may lead to injury. In the proposed system the cable is fed continuously. There is no "end" of the cable and the system is thus incapable of producing these impulses.

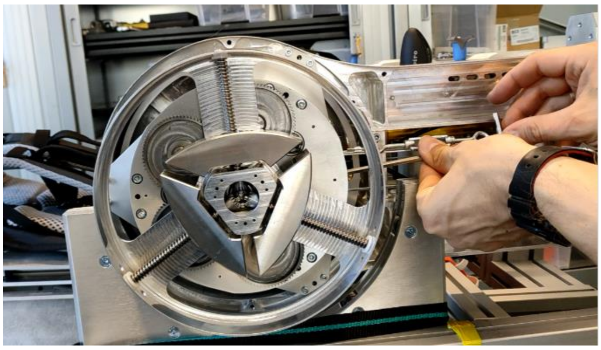


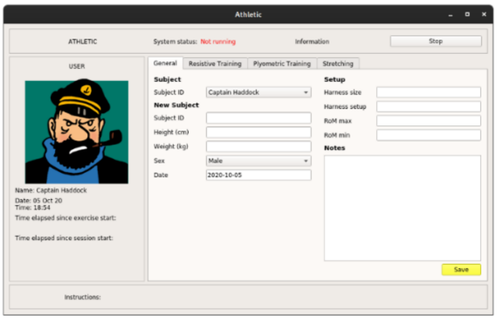
Figure 13. Inertia module – Initial testing.

3.4. CONTROLLER AND INTERFACES

The graphical user interface (GUI) subsystem is including all graphical interfaces for the user. The GUIwill be able to provide all the relevant information to the user including:

- User parameter input table (Fig. 14);
- Description of the training procedure that the subject should follow;
- 2D display of the training parameters and the relevant measurement variables (Fig 15);

The information available and displayed during the exercise is selectable by the operator. The user is able to input commands and interact with the system before and during exercises.



System status: Not running

Subject ID: Captain Haddock

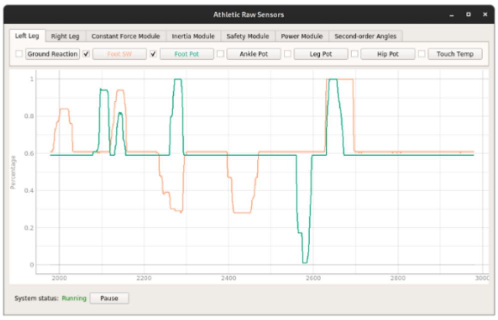
Sex: Male

Date: 2020-10-05

Name: Captain Haddock

Date: 05 Oct 20
Time: 18:54

Figure 14. GUI – User settings.



System status: Running

Figure 15. GUI – Sensor readings.

All sensors information are received at 1kHz update-rate. This allows for adequate analyses even fast motion such as jumping sequences.

3.5. USER INTERFACE ADJUSTMENT FEATURES

As shown in Fig. 16 the body harness can be adjusted in two linear directions (indicated by red arrows). This feature allows to calibrate the user’s torso-position such that the COG of the user is in line with the BTA joint. Both directions are driven by active drive units to increase usability within the clinical tests.

As adjustable seat interface a bike saddle is used. The saddle is adjustable as well to meet the required comfort and optimal position of the user inside the device.

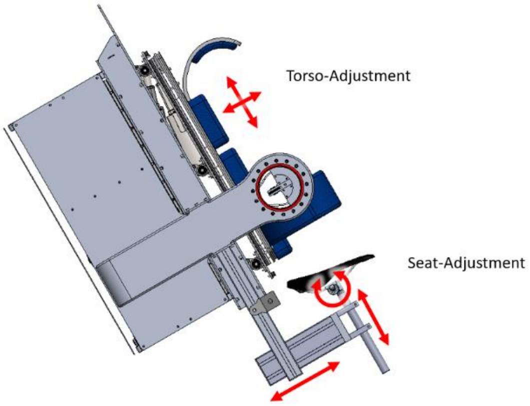


Figure 16. User size adjustment features.

The seat interface is necessary for use on ground (1g environment) especially to avoid that in sitting position g-force pulling down the upper body and sliding of the body harness. If the device would be used in 0g environment the seat interface can be removed.

3.6. GROUND SUPPORT EQUIPMENT

The Mechanical Ground Support Equipment (MGSE) corresponds to all the elements required during the clinical tests to simulate the correct functionality of a device. The concept of the ATHLETIC exerciser has been designed for use in space but can be tested on ground despite the effect of the gravity vector.

The MGSE is a long bed-shaped aluminium frame that supports the user weight while allowing for jump types motions and resistive exercises (see Fig. 17). The support of the horizontal jumping motion is fully passive. The MGSE is also equipped with electric motors allowing for adjusting the angle of the hip position (BTA-joint angular). This motion is done only during the setup of the device and not during the active jump exercises.

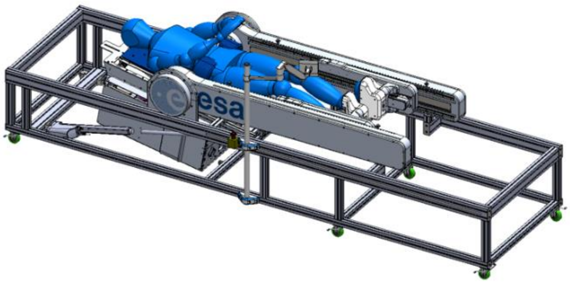


Figure 17. Horizontal MGSE frame.

The back frame supports the user upper body and can be inclined from 90 deg. (sitting position) to 0 deg. (laying position).
This adjustment allows testing the jump capabilities and resistive training of the ATHLETIC device in several hip angles. The hip angle has a direct influence on the muscles activations and the properties of the jump exercises.

4. SCIENTIFIC EVALUATION

The project is split into three design iterations. Each iteration starts with the system design followed by manufacturing, integration and technical testing and is closed by a clinical validation campaign with a set of test subjects. Safety aspects are continuously reflected and analysed as transversal tasks across all iterations.

Out of the three iterations, we have currently finished the second iteration (Fig. 18 and 19 showing the ATHLETIC system setup at DLR) and have started the implementation of updates and facelifts to the system to refine its performance, comfort and usability.

In the final clinical validation, we will compare biomechanical properties and physiological reactions of the plyometric exercises and resistive training on ATHLETIC with conventional countermovement jumps and hopping on a platform measuring ground reaction forces and with weight lifting using a Smith machine. Ten subjects (5 males and 5 females, age between 18 and 30) will visit DLR on 2 days, respectively. Day one: medical check, familiarization with the ATHLETIC device, control jumps and hops, and determination of the one-repetition maximum force for squats and heel raise. Day two: subjects perform the whole set of corresponding tests on the ATHLETIC exerciser.

In a final phase of the project the results of all three iterations focusing on various aspects are analysed and reflected such that the usability and performance of the ATHLETIC device can be finally evaluated and compared with other existing countermeasure devices such as the systems used on the ISS.

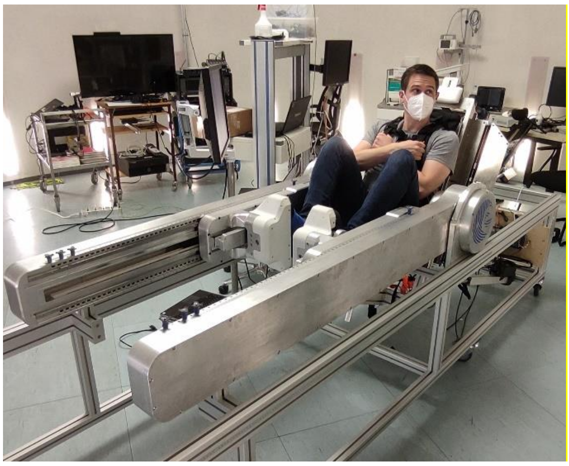


Figure 18. ATHLETIC system @ DLR for clinical testing – front view.

Figure 19. ATHLETIC system @ DLR for clinical testing – rear view.

5. CONCLUSION

The paper at hand presents the novel exoskeleton based countermeasure device ATHLETIC which aims at compensating for muscle and bone loss as an effect of extended stays in 0-g environment.
Exercises like HIRT and plyometric exercises have been presented which are able to perform with the ATHLETIC device. Technical aspects such as the applied anthropometric kinematic, telescopic leg design and applied drive systems has been discussed by introducing each sub-system and giving rationales on the related beneficial performance aspects. Finally, the scientific evaluation at DLR has been presented briefly, additionally pointing out that the ATHLETIC project is split in three design iterations and currently heading towards the last iteration and final assessment of the performance characteristics of the ATHLETIC device.

6. ACKOWLEDGEMENT

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6. Patent application number EP22170624.5