Executiv Summary
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Elysium Industries

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1. SCOPE

This de-risk activity aimed to evaluate the feasibility of using an exoskeleton for astronaut training to counteract the negative effects of microgravity on muscle mass and bone density. The exoskeleton's unique advantages include personalized training with feedback on exercise execution and force levels at each joint, as well as the ability to wear the device for extended periods and train during other tasks, reducing dedicated exercise time.

The exoskeleton should replicate exercises performed on the ARED (Advanced Resistive Exercise Device) on the International Space Station (ISS).

The device's exercise functions have been defined based on ARED training exercises including squats (160kg), deadlifts (160kg), heel rises (180kg), and bench presses (100kg). For the de-risk phase, lower limb exercises have been selected with following adjustable loading:

- Squat (50-160kg)
- Deadlift (50-160kg)
- Heel Rise (50-180kg)

In terms of ergonomics, the device is designed to accommodate a wide range of users, from the 5th percentile Japanese woman (149cm) to the 95th percentile American male (190cm) during the final design phase. During the de-risk phase, it should be suitable for users ranging from the 5th percentile American male (170cm) to the 95th percentile American male (190cm). User acceptance and comfort are paramount, with a focus on minimizing longitudinal forces and localized pressure on the user's body to ensure comfort before, during, and after exercise. Attachment points have been carefully considered with this in mind. Additionally, users should be able to put on and remove the device within 2 minutes without requiring external assistance.

When it comes to torque characteristics, the device is engineered to replicate the torque characteristics of the above-mentioned key exercises. Synchronicity in executing exercises over multiple joints (at least 2) is crucial, with kinematic solutions prioritizing passive synchronicity, although control systems can be employed.

In terms of weight, the overall system weight is targeted to be less than 25kg per crew member, which includes control and power equipment. Individual equipment weight should be lower than 5kg, with considerations made for individualized harnesses if needed.

Power consumption is carefully managed, with peak power expected to be below 200W and average power below 100W.

Safety is a top priority, thus adjustable stops are implemented to limit maximum joint movements and angles, preventing them from exceeding defined limits.

In terms of design, the device employs a cable-based system utilizing fluidic muscles (specifically, commercially available Festo DSMP 40) to control torque at each joint. Cable length and spring tension play a critical role in determining torque.

2. DEMONSTRATOR CONCEPT

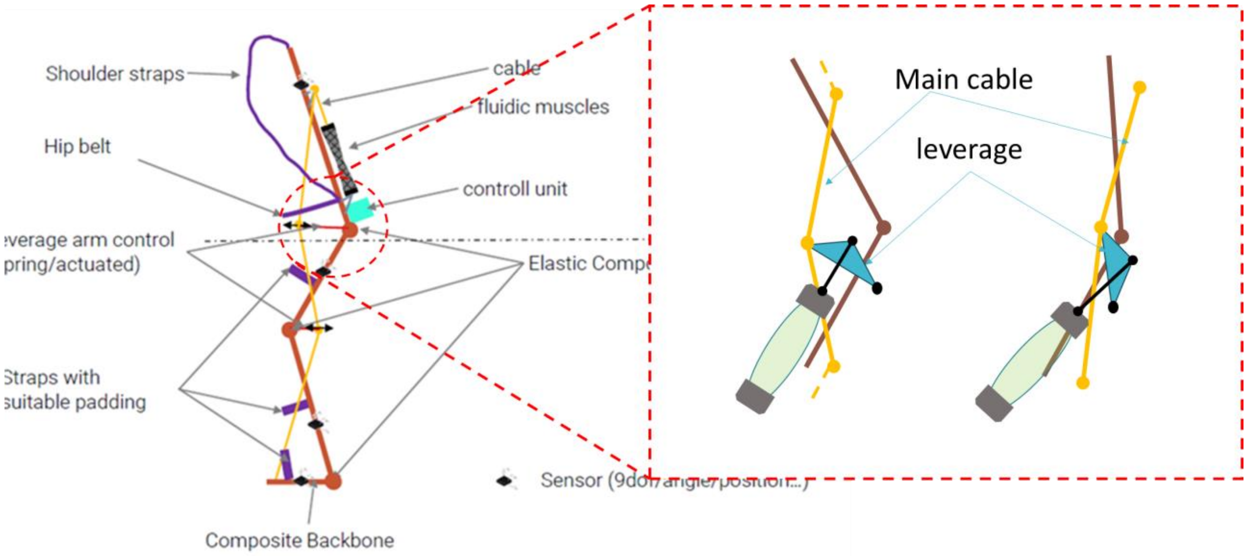


Figure 1 kinematical principle

Leverage arms are strategically used to optimize torque characteristics. The load-carrying elements are constructed from 5mm aluminum sheets, with a particular focus on a critical element for thigh muscles. Dyneema rope with an 8mm diameter is used to replace stainless steel cable, allowing for smaller bending radii. Joints have specific degrees of freedom, with 1 degree for knee and ankle and 2 degrees for the hip. Leverages and bearings are thoughtfully designed to minimize friction, and adjustable stops are employed to restrict joint movement.

3. DEMONSTRATOR

The actuation system relies on fluidic muscles from Festo (DSMP 40) to deliver up to 6000N of force, with a maximum internal pressure of 6 bar. Magnetic valves are used to control muscle pressure, driven by MOS-FETs. The system includes a compressor and pressure tank to ensure an adequate energy supply, and pressure control mechanisms guarantee that the system operates within the desired range.

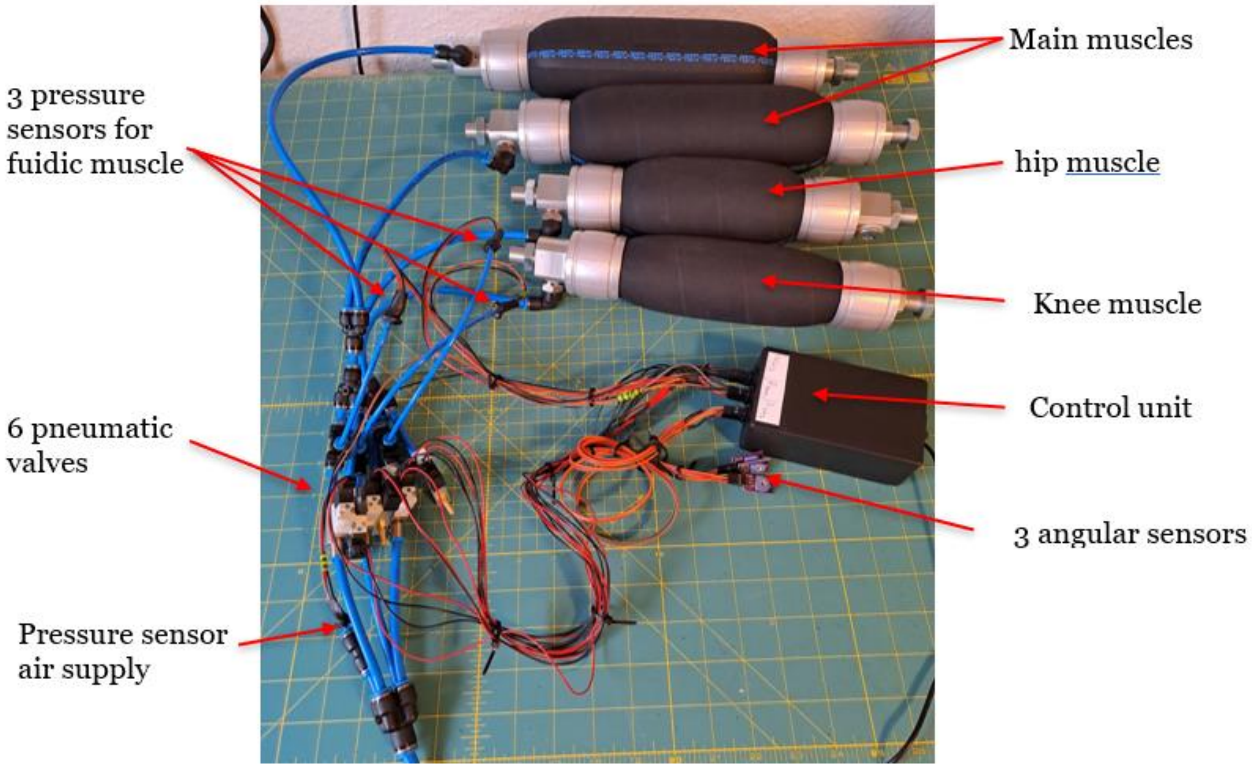


Figure 2: control and actuation system

The control system utilizes an adafruit Arduino board, expanded with additional ADC channels for sensor inputs. Sensors include pressure sensors and angular position sensors. The system communicates with the user via an OLED display and can be controlled through Bluetooth from a mobile device. Pressure control strategies are implemented to maintain the desired muscle pressures. In summary, the design and specifications of the device prioritize user comfort, safety, and functionality while accommodating a diverse range of users. The use of advanced technology, including fluidic muscles and control systems, ensures efficient and effective performance in simulating key exercises for astronauts.

The actuation system has been tested independently of external forces, confirming its functionality. Pressure sensor placement was optimized by moving the sensors closer to the muscles. Control strategy adjustments reduced overshooting.

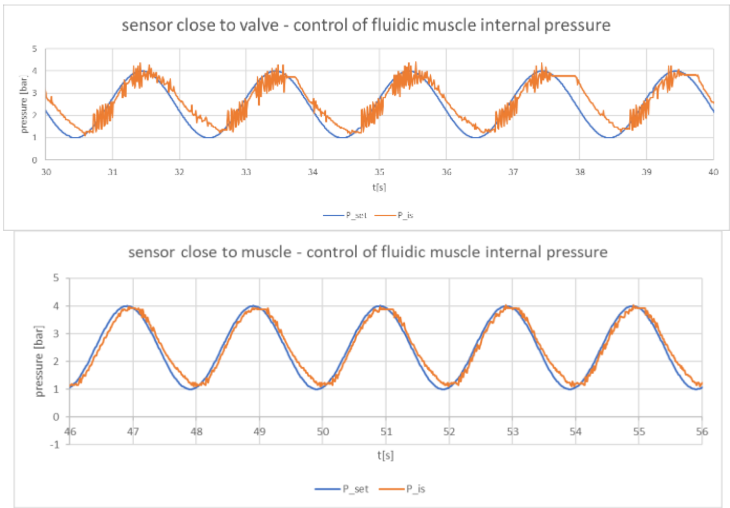


Figure 3: control loop input and response with sensor close to valves (above) and close to muscles (below)

The actuation system can maintain internal pressure with a 50ms reaction time, though further adaptation may be required for the final configuration.

All major structural parts were virtually tested to ensure structural integrity and safe operation. Minor modifications were made, including changes in wall thickness and hole size. These changes ensure that all loads can be carried with a safety factor of at least 2.

In safety testing, all joints were set to their maximum positions under the maximum forces the device can generate. This validated the functionality of all safety stops, ensuring that the device cannot assume unergonomic or harmful positions. The emergency shutdown system was also tested successfully, providing predictable and non-abrupt pressure release times. However, risks of trapping and bruising were identified, necessitating further safety enhancements.

3.1. Verification

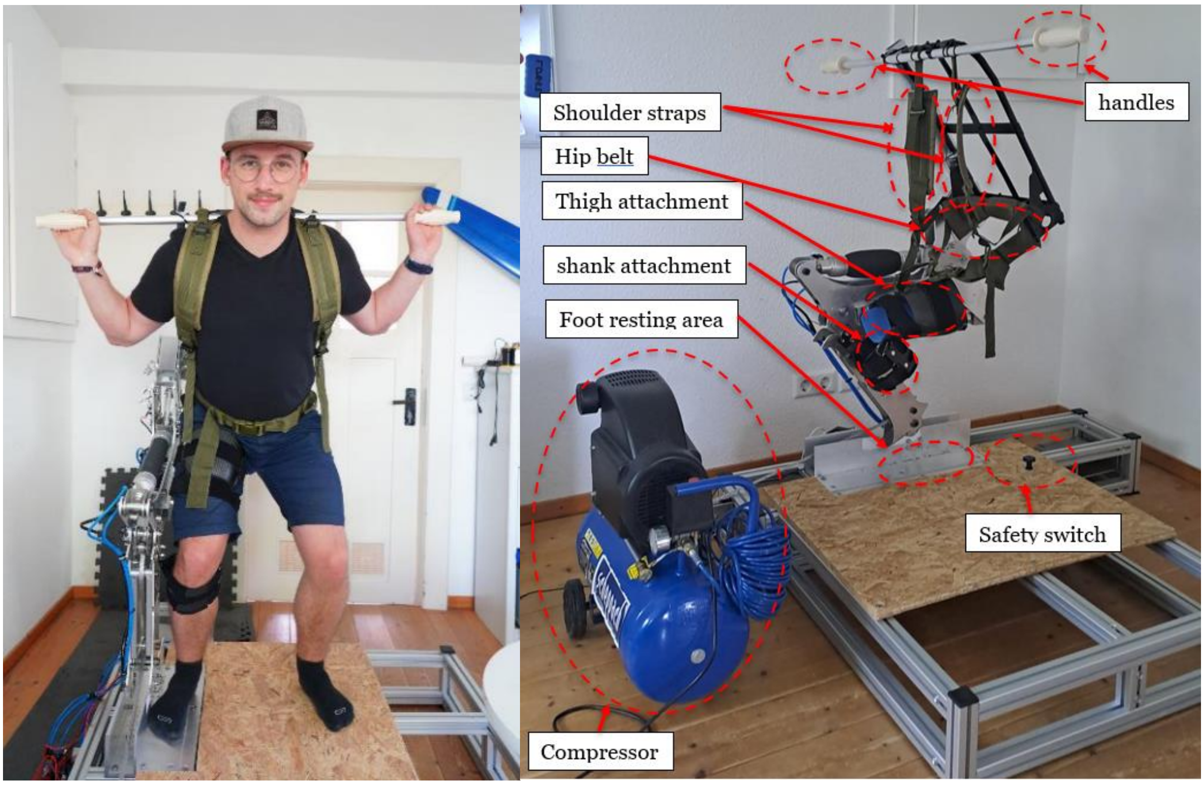


Figure 4: demonstrator

Functionality was evaluated using fixation structures to measure forces in joints and levers. Torque characteristics were tested at different settings (low, medium, high), meeting requirements but requiring slight adjustments for improved accuracy.

Ergonomic testing faced limitations due to unsymmetrical loading and ergonomic issues in certain joints. Additional padding in the back and neck area was recommended for future variants. Size adaptability was verified for various body sizes through measurements and tests with different users. Photographic documentation of adjustments was conducted for two male users.

Users did not report significant issues with longitudinal forces or skin friction during limited exercise times. However, further investigation and optimization are recommended for future iterations. Local pressure issues around the upper thigh harness were addressed by adding a semi-rigid cover, resulting in improved fixation and lower localized pressure. Further harness system improvements are needed. Don/Doff times met minimum requirements with user assistance, but achieving single-handed operation should be a goal for future development.

The demonstrator's total weight was measured at 77.7 kg, with the device itself weighing 56.7 kg and the compressor weighing 21 kg. The system's weight distribution and asymmetrical loading were noted as areas for improvement in future iterations. Power consumption was measured for both the pressurized air system and the electric control system. Recommendations were made for optimizing the selection and design of pressurized air components to achieve lower average power consumption.

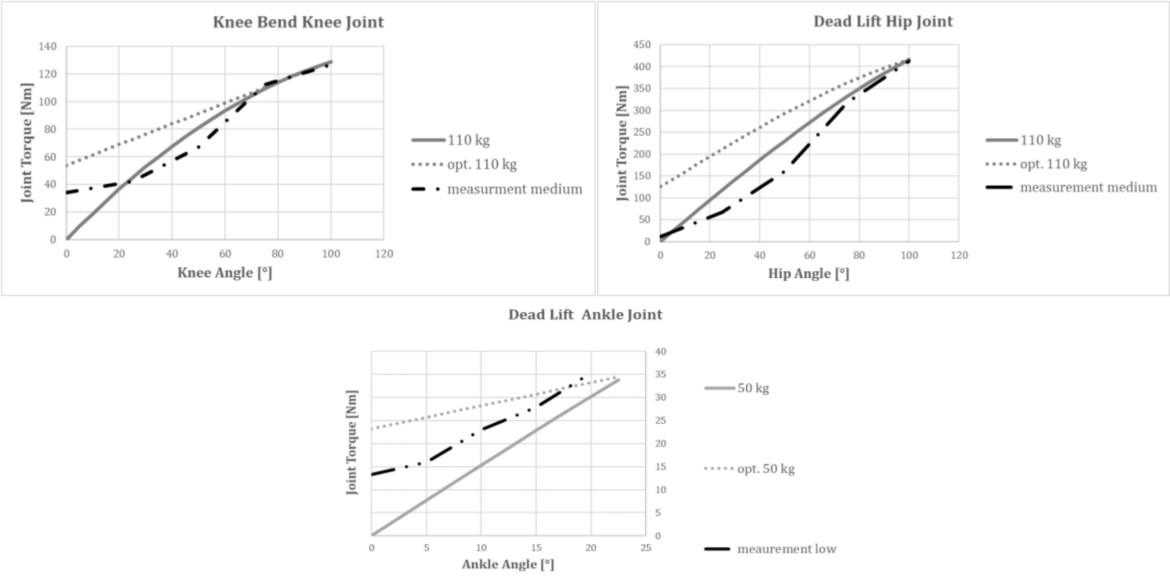


Table 1: torque characteristics

In conclusion, the main functionality of the demonstrator system has been verified, but further adaptations and optimizations are necessary for future phases. These include addressing constraints due to the one-sided design, optimizing for lightweight materials, and developing a double-sided version with balanced loads. Additionally, simulating microgravity conditions for testing is a priority for the next project phase.

4. ANALYSIS

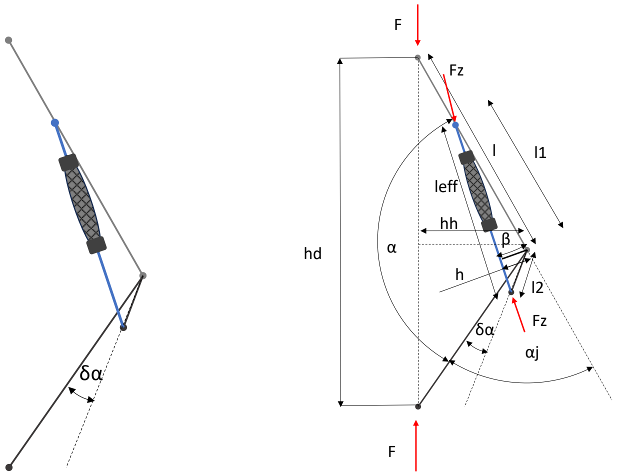
The demonstrated concept for the Elysium Space Trainer has both advantages and disadvantages. One major advantage is its ability to provide individual torque control at each joint, allowing for personalized training and compensation for individual restrictions or injuries while still maintaining training for other joints. It also offers the potential to experiment with different torque characteristics, although rigorous testing is necessary to ensure safety. Additionally, the demonstrator structure is relatively lightweight compared to existing devices like the ARED, and further weight optimization is possible.

However, there are significant disadvantages to this concept as well. It is not feasible to expand this principle to the shoulder and arm due to the complex movements of these joints. This limitation would require excluding exercises like the deadlift from the training program. The ergonomics and usability of the device with multiple fixation points on the body are suboptimal, and while improvements are possible, it will likely remain more complex than the existing ARED, which is more user-friendly. The complex kinematic structure with multiple moving parts and wear-prone components, such as the dyneema rope, results in a labor-intensive adjustment process for different user sizes and requires regular servicing with numerous parts and relatively long service periods.

Regarding requirements for follow-up concepts, the device must cover all exercises currently supported by the ARED, including Dead Lift, Squats, and Heel Raise, with controllable loading up to 2700N. In terms of ergonomics, it should support single-handed operation, quick adaptation for users of different sizes or exercises within one minute, and a focus on low Don/Doff effort and times. Safety and performance requirements remain consistent with the original approach, with no additional requirements for loading, energy consumption, or wear and tear.

Concept Development

Three alternative concepts have been explored. Concept 2 simplifies the structure by using an alternative principle, with control of the fluidic muscles allowing for torque control within acceptable deviations.



$hd = 2 * \sin(\alpha) * l$

$leff = \sqrt{l1^2 + l2^2 - 2 * l1 * l2 * \cos(\alpha + \delta\alpha)}$

$\beta = \arcsin(l2/leff * \sin(\alpha + \delta\alpha))$

$h = \sin(\beta) * l1$

$Fz = f(leff, leff0)$

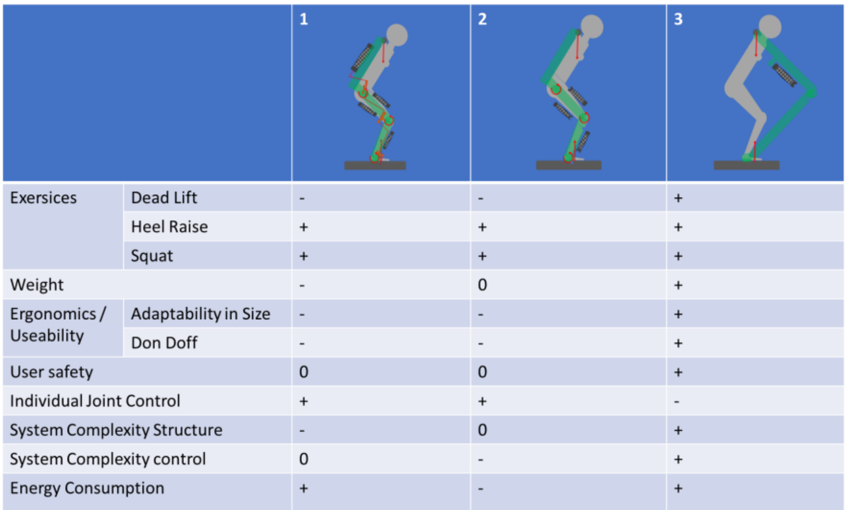
$M = Fz * h$

$F = M/(\cos(\alpha) * l)$

Figure 5: alternative Principle and calculation basis for concept 2 and 3

Concept 3 further simplifies the structure, resembling the ARED device with only one joint and two body fixations. It also uses the alternative principle with three fluidic muscles, offering passive mode operation and adherence to exercise requirements.

Concept analysis indicates that Concept 3 is the preferred option due to its simplicity and compatibility with all exercises. However, it lacks individual joint control, a feature present in Concept 1 and 2.



		1	2	3
Exersices	Dead Lift	-	-	+
	Heel Raise	+	+	+
	Squat	+	+	+
Weight		-	0	+
Ergonomics / Useability	Adaptability in Size	-	-	+
	Don Doff	-	-	+
User safety		0	0	+
Individual Joint Control		+	+	-
System Complexity Structure		-	0	+
System Complexity control		0	-	+
Energy Consumption		+	-	+

Table 2: Concept Analysis

The proposed concept for follow-up phases is Concept 3, however there is one major drawback - the lack of individual torque control on joint level, reducing the possibility to adapt trainings on joint level for injured astronauts for example. This need should be discussed with ESA specialists before starting the next phase. Concept 3 is estimated to have a total system weight of 34.5 kg.

5. CONCLUSION

In summary, the Elysium Space Trainer concept offers various advantages, such as lightweight carbon fiber components, multifunctionality, exercise efficiency, and adaptability. It also ensures functional safety and meets performance parameters for astronaut training. The follow-up plan involves further development and qualification of the space trainer for advanced applications in space missions, with the ultimate goal of achieving TRL 8 with testing in microgravity environment. Estimated budget is 750k€ for phase 1 (TRL7) and 1250k€ for phase 2 (TRL8). The proposed concept does not follow an exoskeleton approach, but uses the demonstrated technology in a more simple and lightweight way, enabling a more versatile usage in terms of resistive training.