Lessons Learned on Design of an Astronaut's Countermeasure Exerciser Device: The ESA NEX4EX and ATHLETIC Projects

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ABSTRACT

During spaceflights, the human body is subject to physiological adaptations to the microgravity environment. Such disturbances may impact operational activities, and thus compromise crew health, performance and the overall mission success. Thus, intensive daily fitness exercises are required for astronauts to remain functional in space. Significant medical progresses have been made since the beginning of the human presence in space, greatly improving the exercises protocols and therefore the health recovery of the astronauts. However, current countermeasure exercise protocols are time consuming, and have to be adapted to the new requirements of the post-ISS missions, toward deep space explorations and the low Earth orbit commercial space stations.

The ESA projects NEX4EX "Novel Exercise Hardware for Exploration" and ATHLETIC "AstronauT HeaLtH EnhancemenT Integrated Countermeasure" succeeded in developing, integrating and validating two advanced multipurpose robotic exercisers. Based on two different kinematic and design approaches, they address neuro-muscular, sensory-motor and musculoskeletal deconditioning by enabling full-body, high impacts and resistive trainings as well as postural exercises within shortened crew time slots.

The two systems were deployed to the DLR Physiology Laboratory for clinical campaign evaluating the training efficiency as countermeasure systems. The clinical tests have shown valuable physiological results in terms of muscle solicitations as a function of the selected exercises.

This paper presents the recommendations and the lessons-learned from the design, integration and testing activities of NEX4EX and ATHLETIC projects in the perspective of developments of further flight countermeasure systems.

1. INTRODUCTION

For long-duration missions, daily fitness procedures are required to counter the effects of living in microgravity [1]. These actions and the related exercise devices are collectively termed countermeasures. Effective countermeasures are necessary for astronauts to successfully to remain functional in space, able to react to emergency situations and to ensure minimal post-flight rehabilitation upon their return to Earth [2]. In particular, so-called plyometric types of exercise, i.e. movements such as hopping or reactive jumping have proven highly effective for maintaining musculoskeletal integrity. On the other hand, exercisers should minimize risk and discomfort.

Therefore, the Space Agencies are now focusing on the development of new generations of exerciser devices, fitting in the constrains of the future planetary missions. This requires the countermeasure systems to be multipurpose and versatile in terms of exercises, providing the necessary stimuli to preserve the full body functionality, added to a smaller footprint compatible with the most recent spacecrafts and the future deep space stations.

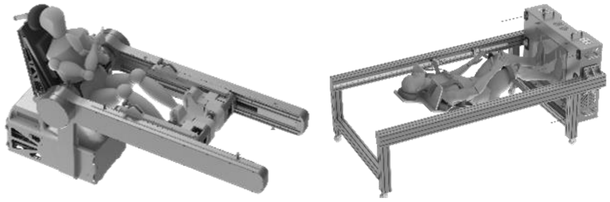

Figure 1. The ESA ATHLETIC and NEX4EX models

The concepts of the NEX4EX and ATHLETIC systems, shown in Fig.1, were based on requests from the European Space Agency (ESA) for study and design of highly integrated systems with focus on addressing neuromuscular, sensor-motor and musculo-skeletal deconditioning.

Compared to existing countermeasure devices, these systems targeted higher and more natural stimulations with solicitations of the full-body during the plyometric exercises while offering combined sensory-motor trainings during postural exercises. They also targeted being directly compatible with the more traditional resistive exercise programs in a compact form-factor.

1. MEDICAL JUSTIFIACTIONS AND SYSTEM BENEFITS

1.1. *Medical's Motivation and Context*

The main effects of deconditioning related to bone loss, muscle atrophy and neuromuscular performances occur critically in the lower limbs but are also directly affecting the full body [3][4]. This is mainly due to a nearly complete withdrawal of mechanical loading when living in microgravity environment.

Similarly, the deconditioning of postural reflex responses affects all trunk muscles and especially the core stabilizing muscles of the lower back. This can result in muscle atrophy, spine deconditioning and the frequent occurrence of back pain [5][6]. Various exercises strategies can be considered for countermeasure [7][8]:

1.2. *Jump and Plyometric Exercises*

Plyometric training refers to countermovement jumps and forefoot hopping. These jumps are characterized by an almost maximal power output during leg extension, and by the greatest achievable musculoskeletal stresses. Hopping includes short phases of eccentric muscle contraction, which stretch the muscle-tendon complex, store elastic energy and trigger a reflex muscle activation that helps to potentiate power output.

Plyometric exercises exert short impacts in terms of rapidly increasing forces. When the muscle-tendon units 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 [9]. For the lower body this type of exercise mostly consists of jumping exercises such as squat jumps, hopping or power skips [10].

During the short ground contact, peak forces occur which are approximately three times higher than the loads possibly used during the relatively slow motion of resistive strength training [11]. Therefore, jumps provide a much higher mechanical stimulus for bone formation than classic exercises used in strength training. Maximum jump training further results in neuromuscular skills needed for the development of short explosive power movements, a skill that cannot be reached or conserved by other measures like treadmill running [12][13].

1.3. *Postural and Sensorimotor Exercises*

The training of postural control reflexes aims to avoid the deconditioning of this aspect of sensorimotor control. It targets the reduction of the stabilizing back musculature atrophy which is less covered by standard strength trainings in space [14]. During training of the postural control reflexes, subjects are asked to maintain a stable standing posture while being stimulated by a set of perturbations at the shoulder or and standing on a unstable feet plate.

1.4. *Resistive Exercises*

Highly Intensive Resistive Trainings (HIRT) follow the principle of moderate overload. They essentially represent slow and safe strength training for activating muscle growth.

For the lower body, examples of HIRT are squats, heel raises or leg press training. Loads are normalized on the subject's body weight at 1*g* 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.

2. SYSTEM DESIGN AND MANUFACTURING

Following the results of the initial studies and from the recommendation of the medical teams, both NEX4EX and ATHLETIC projects have comprehended the full design process with extended user's scenarios analysis and requirements definition. The detailed concepts were then validated with support of musculoskeletal inverse dynamics simulation frameworks.

However, even if they are based on similar clinical objectives, NEX4EX and ATHLETIC were designed with some different conceptual approaches:

2.1. *NEX4EX Concept and Kinematics*

The NEX4EX device is a highly compact system, designed around a main frame located under the feet of the user.

Figure 2. The ESA NEX4EX system without its MGSE

The foot platform (see Fig.2) is protecting all the sub-modules, including four postural stimulation motors, a low-frequency oscillating ground-reaction plate and two passive artificial gravity generators as well as all the onboard control electronics and computers units. The Figures 3. presents the different training setups for the NEX4EX device.

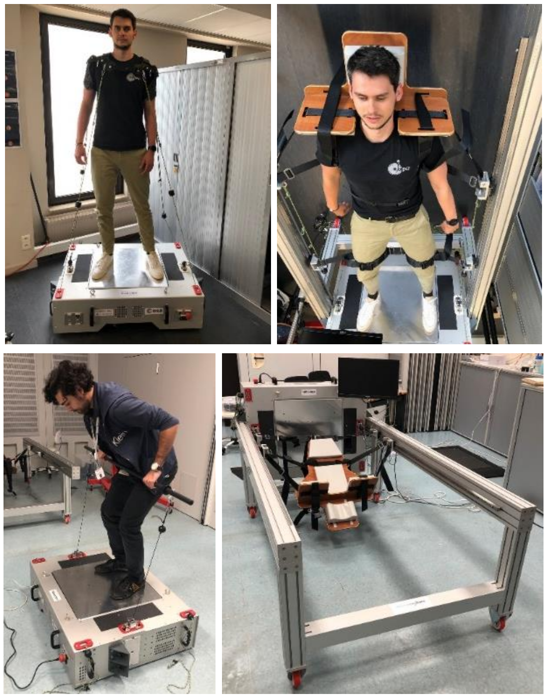

Figure 3. NEX4EX exercises modes (Top-left to bottom-right: Postural training, Plyometric training, Resistive exercise and MGSE ground test platform)

During the plyometric exercises, the body harness located at the user's torso transfers the forces generated by two spring-driven constant-force mechanisms. The desired loads are adjustable to simulate gravitation forces during jumping and hopping (min 10kg – max 140kg of constant force).

For the postural exercises, four ropes are attached to the shoulder harness. They generate the variable impulses perceived by the user as sensorimotor stimulus in two planes of motion (X-axis and Y-axis) and replicate a Z-axis gravity loading. Inside the foot platform, four motors control in real-time the tension on each rope. This system generates an unbalanced gravity vector which the user will have to actively compensate to maintain his/her standing posture. The footplate is generating additional randomly variable frequency perturbations in the X-axis, enhancing the feeling as instability for the user.

As part of the Mechanical Ground Support Equipment (MGSE), two passive guide rails and a horizontal jump sledge maintain the torso and legs along the main movement axis, perpendicular to the foot contact surface. The side rails are mitigating the risk of injury during high dynamic movements like jumping and maximum hopping by preventing the rotation of the user's body with the platform (max jump height 100cm). The horizontal position also supports the user's weight during the ground tests.

2.2. ATHLETIC Concept and Kinematics

The ATHLETIC system is combining a pseudo-anthropometric exoskeleton structure with semi-passive actuation [15].

Two linear rails which are positioned on each side of the user's legs (presented in Fig.4). Using linear rails to transfer loads to the user's feet is beneficial when dealing with high forces in the kinematic chain. Each leg features a ground reaction plate that allows a natural motion and forces transduction toward the user's foot.

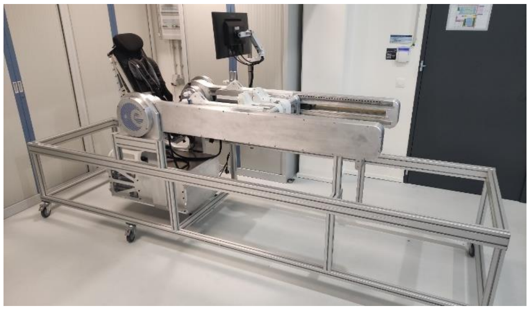

Figure 4. The ESA ATHLETIC system inside its MGSE

The telescopic legs supports all kinematic elements to guide and load the user legs. The back module contains the two constant force drive modules and the avionics. The drive modules simulating inertia loads are embedded into the telescopic legs.

The Figure 5. shows the full kinematic profile of a jumping leg within the ATHLETIC system. The telescopic legs are equipped with sensors to determine linear and rotary joint positions as well as to detect the ground reaction forces.

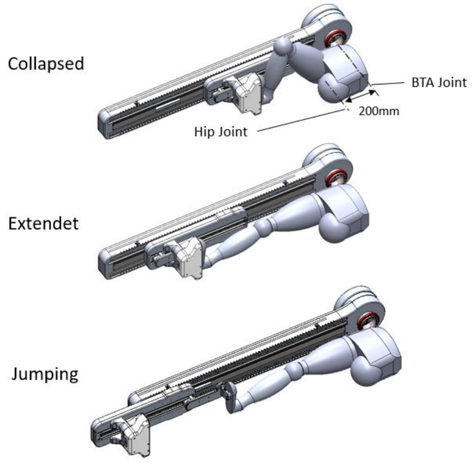

Figure 5. ATHLETIC jump kinematics

There is no need of braces or any other thigh fitting connections between the legs of the user and the exoskeleton. The user is only attached to the device by a torso harness and shoes-locks restraints.

2.3. *Constant Force Module*

The Constant Force Mechanism (CFM) is novel drive system implemented in both the NEX4EX and ATHLETIC exercisers. It is at the core of the gravity simulation loading of both devices. The CFM are passive actuation systems that allow to simulate constant but adjustable g-load.

This unique drive solution supports the following benefits:

- Drastically reduced electric energy consumption,
- More explosive exercises are possible compared to traditional active actuator solutions,
- Inherently increased safety as it is purely mechanical system (no software or motor control related risks),

These modules are able to create forces of maximum 750N and a maximum wire displacement of 1000mm toward the outside of the system. They buffer the potential energy from the user's exercises in a set of mechanical coil springs [16][17]. Picture and rendering of the mechanism itself is shown in Fig. 6.

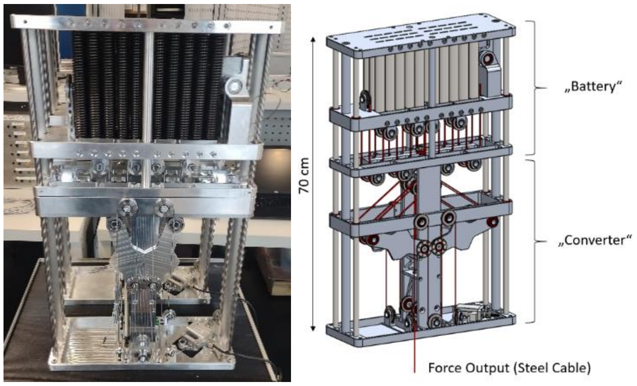

Figure 6. Constant force module

The combination of small moving masses and local internal 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 external high speed motion accelerations and velocities such as expected during jumping motions.

3. SCIENTIFIC EVALUATION AND CLINICAL TESTS

We then tested the acute physiological reactions created by each devices through the different training modes on human subjects at the DLR Institute of Aerospace Medicine. The scientific evaluation was further focused on sufficiently high training stimuli, safety, reproducibility, and reliability of the technical performances.

3.1. *Scientific Evaluation Study*

The examination was composed of 10 healthy subjects (4 males and 6 females, age between 30 and 60, see anthropometric data in Table 1) on two days each. Subjects were fully acquainted with the experimental approach and provided a written informed consent prior to their participation. Approval was issued by the North Rhine Medical Association's Ethics Committee (Ethikkommission der Ärztekammer Nordrhein, Düsseldorf, approval no. 2019369).

	Total (n=10)	Women (n=6)	Men (n=4)
Height [cm]	176.6 (158 – 193)	170 (158 – 180)	186.5 (180 – 193)
Weight [cm]	73.8 (53 – 93)	66.8 (53 – 85)	84.3 (75 – 93)
Shoe Size	41.6 (36 – 47)	39.2 (36 – 42)	45.3 (44 – 47)

Table 1. Clinical tests anthropometric data

For each subject, the first visit included the medical check, control jumps and hops, and the determination of the one-repetition maximum force for squats and heel raises on a Smith machine. The training intensity was set during resistive training to 150%BW by adding barbells during Squatting and Heel Raises. Plyometric training was done with 100%BW. The EMG amplitudes during NEX4EX/ATHLETIC exercising was related to the EMG amplitudes of these reference exercises. In the second visit, the subjects performed the whole set of corresponding equivalent exercises on the ATHLETIC and NEX4EX devices (pictures taken during the clinical tests are shown in Fig.7).

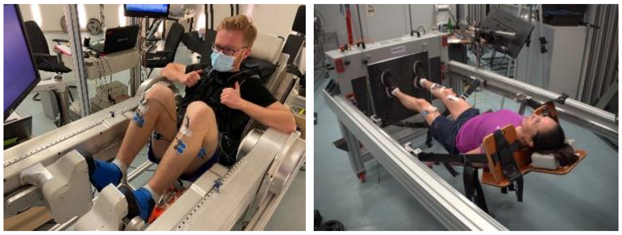

Figure 7. ATHLETIC and NEX4EX during clinical tests

The group of tests subjects was kept the same between the NEX4EX and ATHLETIC studies for direct system comparison between the two devices.

3.2. *System and Physiological Measurements*

During the exercises, the system internal sensor feedbacks and the measured applied loads were recorded at a sampling rate of 1000Hz. The records were filtered with a 10 Hz 4th order Butterworth low-pass filter.

The muscular Electromyography (EMG) activities and physiological reactions of the plyometric exercise on the

two devices were recorded at 2000 Hz sampling rate on a Noraxon telemetry device. The EMG signals were rectified by Root Mean Square (RMS) and underwent a moving average of 501 samples corresponding with 250.5 ms.
In addition, acceleration data from a 3D-accelerometer mounted on the shin (tibial plateau) under the patella of the right leg was recorded.

The results were then compared to reference countermovement jumps and hopping performed on a Leonardo GRFP mechanography jumping platform. Ground reaction force was recorded at 1000 Hz and automatically analysed for peak force, launch velocity, peak power and jumping height.

3.3. *Sensori-Motor Exercises Evaluation*

The sensorimotor training consisted of participants standing upright on the device. The participants were suddenly pulled towards the platform by one of the four ropes that were attached to their shoulder's harness. The force on each rope was increased by approximately 160-180 N over a 500ms timeframe. The participants were instructed to resist the pull and stay in an upright position or return to the upright position as quickly as possible after the pull.

During the second exercises, the platform vibrated in addition at four different frequencies (1, 2, 5 and 10Hz). Participants stood upright on the platform and were instructed to keep their upright position throughout the vibration. We could, however, only detect reliable data for the 10 Hz and 5 Hz condition and were not able to analyse EMG-signals for the lower frequencies.

3.4. *Plyometric Exercises Evaluation*

We tested Countermovement Jumps (CMJ) as well as forefoot hopping on both feet and only on the right foot, respectively. The tests of CMJ and hopping were performed at a constant load and mass inertia corresponding with the subjects' individual body masses. The loads were reduced, when necessary if requested by the test subject.

The results of the EMG analysis show that it is possible to activate the muscles in a comparable manner between reference measurements and plyometric exercising on the devices.

3.5. *Resistive Exercises Evaluation*

The clinical tests on resistive training comprised squatting and heel rises. The reference training was performed with the subjects' own body weight and an extra load of 50% body weight applied by on the shoulders by a barbell. Most of the tested subjects could perform with 30 more repetitions in both modes, heel raise and squats, respectively (see example of squat tests recording in Fig.8). Therefore, the reference training represented a moderately intensive resistive training.

For squatting and heel raises on the ATHLETIC device we aimed at a sum load of also 150% (body weight plus 50% extra) provided by the two constant force mechanisms and coupled telescopes. With uncoupled telescopes knee extension and flexion as well as heel raises were tested on the right leg only.

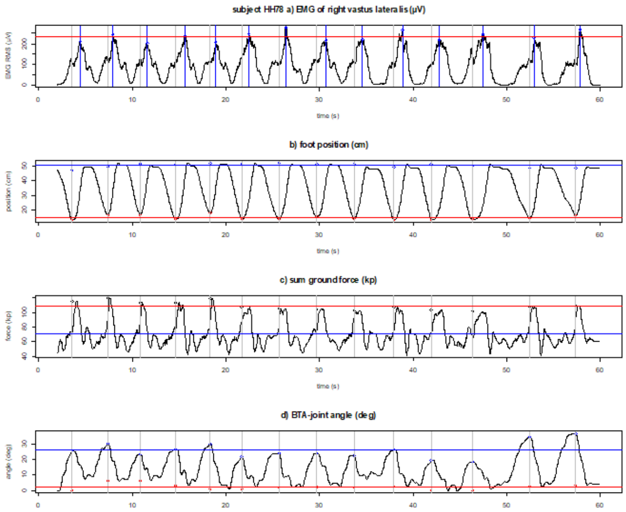

Figure 8. Typical records from a subject during squatting

3.6. *Scientific Evaluation Conclusions*

The clinical evaluation provided key understandings on the two systems, based on the extended feedback received from the direct clinical measurements. Additional feedbacks were also obtained from the test's subject questionnaire regarding user acceptance, ergonomics and system usability targeting user-machine interfaces, body size/force adjustment mechanisms or the Graphical User Interface (GUI).

The evaluation and clinical studies have shown that sensorimotor trainings, plyometric trainings as well as resistive exercising are in principle possible on the two exercisers. They have been be performed by subjects of different age, sex, height and weight, as well as different training status.

It has been observed that is most important that the user of this device gets a good instruction and do have time to familiarize with the device and especially with the movements, which need to be performed. As the aspects are considered, a comparable and effective training will be feasible. For better understanding of the movements, further analysis including assessments of the joint stiffness of the knee joint and ankle could also be performed.

4. PROJECT’S LESSONS-LEARNED AND RECOMMENDATIONS

The parallel developments of the NEX4EX and ATHLETIC systems offered a unique opportunity to have a direct comparison between an exoskeleton based-design versus a more integrated platform-based system.

Both projects succeed in developing, assembling and validating a ground model of a compact and polyvalent device for applications of countermeasure to be used astronauts in space. Several lessons learned and recommendations can be highlighted from the results from the two projects:

4.1. Ergonomics and User Acceptance

The comforts of the body attachment harness were the main source of feedback from the test subjects. It has been noted at several times during the validation tests that inadequate ergonomics or positioning inside the body harness or the device itself had lead to quick discomfort and fatigue, resulting in decreased user satisfaction and abandonment of the equipment.

The NEX4EX harness has been designed for strict system simplification and reliability. Even if it has fulfilled its function and did not failed during all the tests, it was still a low-acceptance due to the lack of comfort and the lack of body size adjustability. As comparison (see Fig.9), a different approach was taken on the ATHLETIC device with the backpack specialist brand DEUTER for designing a custom-made harness. This harness has very well appreciated by all the test subjects over the “wood+foam” harness of NEX4EX.

Figure 9. NEX4EX vs ATHLETIC body harnesses

This clear difference of user acceptance really puts an emphasis on the design of the body harness: a “simple and reliable” design is not the correct approach for a system to be used in very close contact to the body and carrying high loads. The ergonomics played a crucial role in their acceptance of the exercise machines, as it directly impacts their feeling of comfort, safety, and overall experience of individuals using such equipment.

It is recommended that the design of the upgraded body harness is supported by the use of simulation tools (like the Anybody Simulation Framework) for aspects related to comfort and full range of user sizes in the context of a training in microgravity (i.e. with specific loads cases). This simulation should further be confirmed through parabolic flight validations tests. The agencies space medical offices and safety boards can provide an important support for checking and guiding the applications of requirements and guidelines.

The overall user-acceptance was also closely linked to the ergonomics of the interface, GUI and control systems, as intuitive and user-friendly designs was enhance the ease of operation, minimizing user frustrations and therefore can promote a better engagement.

Considering the critical role of user acceptance and long-term motivation in the success of sport machines, integrating ergonomic principles throughout the design and development process is imperative for creating highly functional and well-received countermeasure system. Even if the engineering efforts are usually focused on the internal sub-modules, a proper and high quality body harness is critical for not only user comfort and system acceptance but also even more for the overall system performances.

4.2. Initial System Requirements

Effective system requirements are critical in the design of a flight system to ensure its functional performance and user acceptance. Accurate system requirements contribute to a reliable and safe countermeasure system, reducing the likelihood of malfunctions or safety hazards during its operation.

The development of the NEX4EX and ATHLETIC were based on the preliminary ESA/EAC requirement analysis for future countermeasure exercises, leading to guidelines of design development. For the future flight countermeasure systems, due to the antagonist nature of some requirements (power to weight/volume ratio, stiffness….) and their potential large influences on the design features, it is strongly recommended to obtain an extended operational and performance requirements analysis of in-flight countermeasure exercises. This should be conducted in close collaboration with end-user’s and relevant specialist from the medical offices. The state-of-the-art should then be confronted to the newer detailed requirements to further analyses how to address them (e.g. in terms of required torque, velocities….) and update accordingly.

Then, following the initial phase, a detailed design for the Flight Model should propose a new device that take into account these requirements, correct the weaknesses and addresses critical flight constraints. Among different topics of updated requirements, we can highlight:

- Size and Weight optimization/reduction (could depend on the final application),
- Actuation optimization and integration,
- Mechanical robustness and maintainability,
- User comfort and force interaction/transmission, usability (don-on/don-off, size adjustment),
- Control software algorithms, integration, interfaces with users/operators and external medical tools
- Flight-Model criticalities (e.g. qualification tests).

4.3. User Pre-Training

During the very first tests sessions it was observed that the quality of the exercise's performance was varying distinctly different between subjects. Mainly during the horizontal countermovement jumps movements and squats, they needed to practice the required motion in the new body posture and new physical environment until they were able to coordinate especially the more complex body motion in a natural way. Some subject got confident with the proper motion much quicker than others.

From the first subject on, we learned that the relative complex coordination of motion involving the knees and the hips during squats and countermovement jumps needs some time for practicing at lowest force levels. The subjects must learn that the extended horizontal posture while lying is the new analogue of up-right standing at the beginning of exercise. The simultaneous flexion of knees and hips during squatting was also needs a learning process. During natural squats on ground the flexion of knees and hips follows gravity and subjects used to place the center of their body mass over the forefeet to balance the posture of the body.

Therefore, the effectiveness and safety of exercise routines in countermeasure exercise device heavily rely on pre-training activities designed to properly prepare the body for physical exertion and facilitates better neuromuscular coordination, which further aids in improving overall athletic performance.

The incorporation early of pre-trainings sessions in the pre-fight preparations and even during the mission's exercise protocols is essential for maximizing training outcomes efficiency and minimizing the likelihood of sports-related injuries.

5. CONCLUSION

This paper presented in details the results from the ESA NEX4EX and ATHLETIC projects, designed for supporting the astronaut's daily sport exercises and aiming at mitigating the effects of microgravity during post-ISS missions.

Throughout the two activities, we obtained and developed keys understanding, lessons learned and recommendations in the perspective of next related flight design activities. We have highlighted the challenges of such developments, mainly related to user's ergonomic/acceptance, to the user's pre-training. The complex relation between training requirements (level of torque, required speed…) and needs of compactness and lightweight structure for flight models will be at the core of future developments.

The two device developed during the NEX4EX and ATHLETIC projects successfully demonstrated capability as integrated, multi-functional systems, in the context of space countermeasures. Shared with the teams from ESA/EAC, we hope to further refine and validate the novel developments. We also conclude that future flight countermeasure devices can effectively and safely provide postural and jump training modalities – two important facets of the new generations of astronaut's countermeasure exercisers in Europe.

6. ACKNOLEDGEMENTS

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