NEX4EX: Novel Exercise Hardware for Exploration

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ABSTRACT

This paper presents the NEX4EX project "Novel Exercise Hardware for Exploration", which aims to design, build and validate a full-body countermeasure platform that enables high intensive resistive and plyometric exercise as well as postural control training, and strength training. The NEX4EX exerciser herewith addresses neuromuscular and musculoskeletal deconditioning. The intended use is to improve crew health and fitness maintenance for long-duration space missions beyond ISS lifetime. This will require the system to be multipurpose / versatile in terms of exercises added to a smaller footprint than systems currently used on ISS. NEX4EX is a novel concept for a novel utilization paradigm given future space exploration-class missions.

1. INTRODUCTION

During spaceflight, the human body is subject to physiological maladaptation to the microgravity environment [1] [2]. Such disturbances may impact operational activities, and thus compromise crew safety, performance and overall mission success [3].

Daily fitness exercises are required for astronauts to remain in functional contingency in space [4]. Since the first human space flights, significant progress has been made, and the current set of countermeasure devices and protocols have greatly improved healthy recovery of the astronauts. However, the development of even more compact and multipurpose countermeasure devices, providing the necessary stimuli to preserve the body functionality during extended stays in microgravity environments, is a necessity to fit in the constrains of the future planetary and long-duration missions. It will support the astronaut for a much quicker and enhanced re-adaptation to gravitational forces on Mars or on Earth [5] [6].

This paper introduces the problematics of space countermeasure against the deconditioning of muscle mass and performance and in sensorimotor control of body posture. In this context we describe the expected benefits of the proposed technology. The subsystems are addressed with a focus on design description of the mechatronics elements and the main technical design challenges. It details the simulation analysis that has been used to support the design process.

Finally, the functional testing and the scientific evaluation strategy for the validation of the device performance is introduced.

2. DEVICE EXPECTED BENEFITS

The NEX4EX device, as shown in Fig. 1, is a robotic multi-exercises sport platform. The astronaut will be able to perform the various trainings as recommended by the supervising fitness instructors.

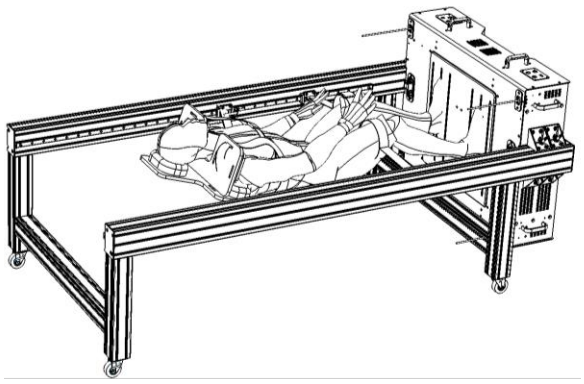

Figure 1. Computer rendering of the NEX4EX exerciser for qualification tests on Earth.

2.1. SENSORIMOTOR EXERCICES

During standing or during various forms of locomotion, postural control comprises a complex system of reflexes that activate the postural muscles to keep the body in an upright position, naturally, against the vector of gravity. The gravity vector is mainly sensed by the macula organs in the inner ears. This information is absent in microgravity. Other neural information, which in principle should be still present in space, is heavily altered by the absence of physical loading in microgravity [7]. The remaining information includes linear acceleration sensed by the vestibular organs, the visual input, and diminished proprioceptive input by mechano-sensors located in muscles, tendons, ligaments and the skin.

Hence, in microgravity, the postural control reflexes, i.e. the muscular response to postural disturbance are not used and undergo deconditioning. Besides the leg and hip musculature, the absence of such a reflex pattern affects mainly the trunk muscles with more degradations observed on the inner and outer muscles of the lower back. This results in muscle atrophy, elongation of the spine by swelling intervertebral discs and frequent occurrences of back pain [8] [9].

The training of postural control reflexes by NEX4EX aims to avoid the deconditioning of this aspect of motor control. It targets in addition the reduction of the back musculature atrophy which is less covered by standard strength trainings.

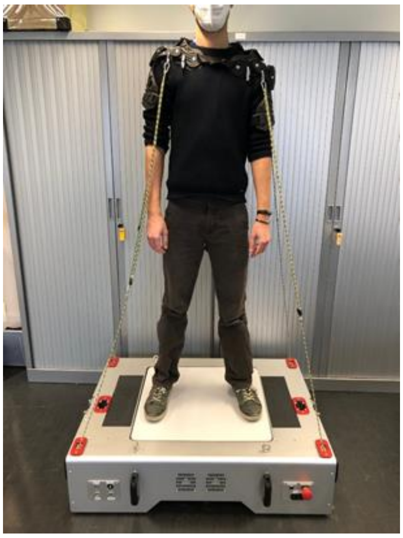

Figure 2. Sensorimotor training on NEX4EX.

During training of the postural control reflexes with the NEX4EX device, the astronauts will be asked to maintain a stable standing posture (Fig. 2) while being stimulated by a set of ropes attached on a shoulders harness and standing on a low-frequency randomly oscillating feet plate.

Fig. 3 presents the system architecture of the sensorimotor setup. The user dons a shoulder harness attached to four robotically control winches located inside the foot platform. The ropes generate impulse perceived as sensorimotor stimulus in two planes of motion (X-axis and Y-axis) and replicate a Z-axis gravity loading. Inside the feet platform, four motors control in real-time the tension on each rope that simulates an unbalanced and tilting gravity vector which the user will have to actively compensate to maintain his/her standing posture.

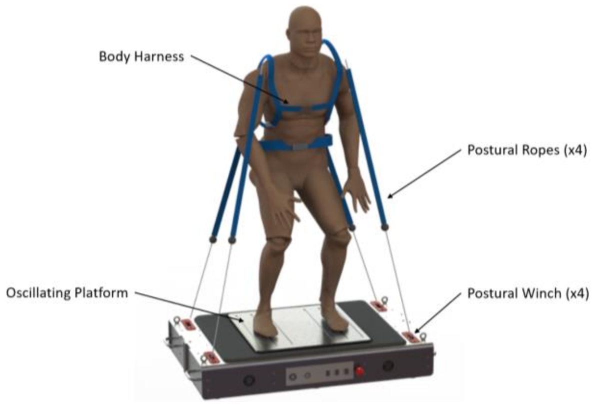

Figure 3. Sensorimotor exercise

The footplate is generating variable and random frequency perturbations in the X-axis, enhancing the feeling as instability for the user.

2.2. PLYOMETRIC EXERCICES

The NEX4EX exerciser covers training of countermovement jumps and forefoot hopping. These jumps require maximal power of the leg extensor muscles and are characterized by short phases of eccentric muscle actions, which cause stretching and reflex activation of the leg antigravity muscles. A concentric contraction immediately follows, which profits from the previous additional reflex activation and a release of elastically stored energy in muscle and tendon.

During the short ground contact, peak forces occur, which are almost four times higher than the loads possibly used during the relatively slow motion of resistive strength training. 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 or resistive exercise.

Gravity independent, plyometric exercises on a horizontal sledge were successfully tested as countermeasure within ESA sponsored 60 days bed rest study with reactive jumps [10] [11] [12]. The short ground contact time of about 150 to 200 ms, the slope of force increase over time, the muscle elongation, and the kinetics of muscle activation have shown that the exercises performed on the horizontal jump sledge trigger similar biomechanically performances as of natural hopping [13]. Shown in Fig. 4, the NEX4EX device will be used in a most similar manner with high loads simulating forces up to 1.5 times body weight.

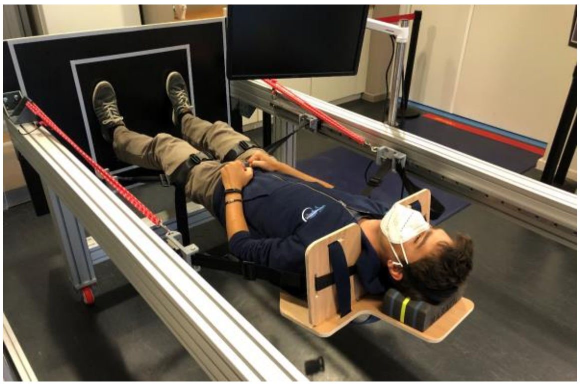

Figure 4. Full-body jump training on NEX4EX.

It has been noted that as the high forces are mainly produced during the braking action (ground contact during jumping), a lower loading force between 80-100% of body weight could still be efficient. It has been shown that this amount of loading is mitigating effects of prolonged unloading [14]. The resulting energy is stored within the muscle-tendon unit and simply translates in an increased jumping height. The efficiency comparison will be evaluated during the clinical trials of the project.

In the NEX4EX device, the naturally gravity driven forces are replaced by two newly developed, spring-driven constant force mechanisms, adjustable to the desired loading. The two side guides are connected to the body harness on the rigid section of the jump sledge (see Fig. 5). The harness transfers the forces generated by the loading device to simulate gravitation forces during jumping and hopping.

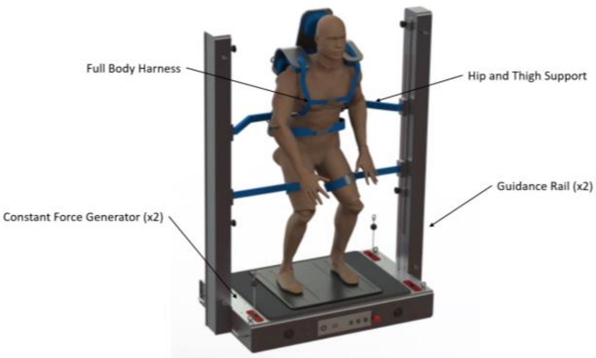

Figure 5. Plyometric exercise

The side rails aim to minimize injury risk during high dynamic movements like jumping and maximum hopping by preventing the rotation of the platform with the body.

NEX4EX allows almost natural flexion of joints along the body axis and will apply sufficiently high, constant forces corresponding with the weights usually applied during intensive jumps and strength exercises on ground sports machines.

2.3. RESISTIVE EXERCICES

On NEX4EX, resistive training includes squats, dead-lift and heel raises to better target the hip and knee extensor muscles. Classical resistive training stimulates muscle growth and strengthening following the principle of moderate overloading.

The training load is adjusted to an individually determined one repetition maximum (1RM), which in a long-term progressive training program is regularly readjusted by the current performance. Resistive strength training includes high loads between 60% and 80% of 1RM a small number of repetitions (e.g. 8 to 15) per set and 2 to 4 sets per session.

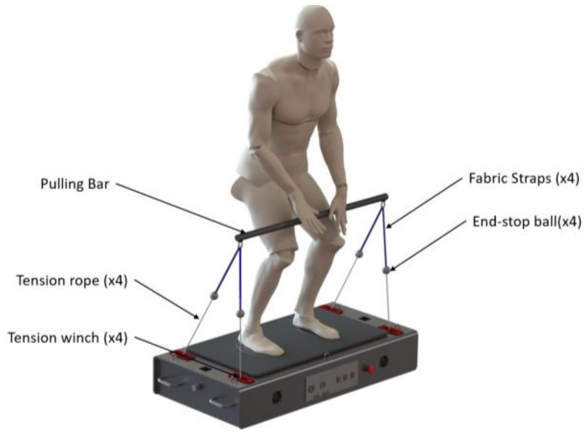

Figure 6. Dead lift exercise

As shown in Fig. 6, for the resistive exercises, the NEX4EX device is equipped with a horizontal bar attached to the module's force generators for providing loading to the users during the pull up or deadlift exercises. In this configuration, the user is asked to lift or pull on the bar. The user is not attached to the exerciser and is not wearing a body harness.

2.4. DEGRADED MODE EXERCISES – LOW POWER MODE

The degraded modes corresponds to a particular situation where the electric power availability from the spacecraft is restricted but the requirements of physical training for the crew are maintained.

The constant force mechanism will be able to generate passive loading force and allows the high-impact training/jump training to remain fully operational. The constant force intensity will have to be adjusted by a manual override system to maintain correspondence to the user's body weight.

The resistive training will as well remain fully operational under the same conditions as the jump trainings.

The postural exercises using the oscillation plate and the postural motors will be compromised.

The On-board Computer could still be operational and able to provide live sensors feedback to the user.

3. ARCHITECTURE AND DESIGN

The NEX4EX device is designed around a single frame located under the feet of the user. All core elements of the device are protected inside the main structure shown in Fig.7.

The user stands on the footplate located at the centre of the module. The plate generates the low-frequency stimulations during sensorimotor training and supports the ground reaction force and centre of pressure sensors plate.

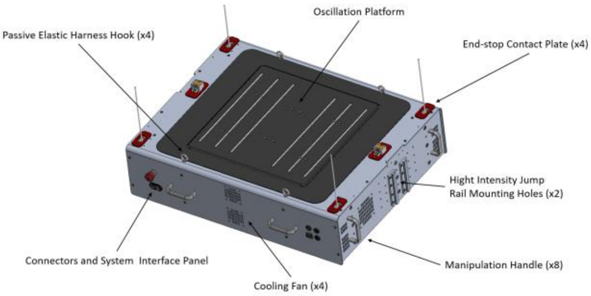

Figure 7. NEX4EX main frame

For the plyometric and jump exercises, the load is transferred to the subject symmetrically by a double constant force mechanism on each side of the main frame.
To generate un-balanced perturbations to the subject during the sensorimotor training, the postural ropes have to be distant from one to the other as much as possible

3.1. MAIN FRAME

The internal structure is made of aluminium plates hollowed for mass reduction, better cable routing and cooling airflow management. The forced air flow entrances are located on the side panels and on the lower cover of the device. A grid pattern prevent any finger or large tools to be inserted inside the device while allowing a correct cooling airflow.

To support maintenance, the bottom panel is designed to be detachable and to provide convenient access to the inner components.
A set of handle is mounted around the frame for in flight manipulations.

3.2. CONSTANT FORCE MODULE

The NEX4EX device includes two constant force generator modules, one on each side of the main frame. Each module is able to create an adjustable force of maximum 750N and a maximum wire displacement of 1000mm to the outside of the system. The maximum energy stored inside the spring package is 750J. The spring package consists of two sets of 10 extension springs.
The module is design around the principle of a 0-lenght spring providing constant rope tension output as a passive force generator.
The cable for the external pulley system uses a 3mm steel wire. The exit is guided by a two orthogonal twin-wheel guiding system allowing the wire to be used under a wide variation of exit angles in case of exercises without the side guiding rails.

3.3. OSCILATING FOOT PLATE

The Low-Frequency Oscillation Foot Plate is based on a modified Galileo System (Novotec Medical). The gear ratio of the driving belt allows oscillations frequencies below 5Hz.

Four load cells monitor the Ground Reaction Forces generated during dynamic movements on the platform and the effective position of the force vector entering the platform surface (Centre of Pressure, Centre of Force). Depending on the mode of operation, summed forces or positions feedback can be derived from these force values.

For safety, the oscillating foot plate is secured by mechanical locks during the high intensity jump exercises.

3.4. POSTURAL WINCHES

During the balance/sensorimotor training, the users will be stimulated by four ropes attached to the sides of the shoulder harness. Each of the postural ropes is pulled by a dedicated BLDC motor located inside the main feet platform. The internal rope mechanism is kept simple to minimize the risks of technology failure under repetitive hard impacts.

Regardless of the load direction (i.e. the position of the subject shoulder is moving during the postural exercises), the rope will always be supported by a hawsehole roller. The four rollers on each side minimize the friction when the rope touches a side of the hawsehole. The ropes themselves are guided internally to the force sensor. The hawsehole force the rope to a known fixed position. The pulling force is measured directly by a force sensor located on the top of the hawsehole frame.

3.5. CONTROLLER AND INTERFACES

The motor controllers use a control approach featuring nested current, velocity control mode and direct current control loop. The current control loop operates

at 40 kHz. The outer velocity loop operates at 10 kHz. A rate of 10 Hz for commands is sufficient given the current parameters of the system. Faster command speeds are possible but the perceived effects would be dominated by the rope dynamics.
This control feedback rate is acceptable since the motor drives do not manage medically relevant information, it only uses engineering data to evaluate the state of the actuators system.

The medically relevant information needed for the physiological data feedback are isolated from the motor controls. They are directly sampled using the dedicated ADC module. It is collected at high frequency - 1 kHz - and timestamped before being sent over to the OBC (shown in Fig. 8). The sensor controller reads the state of the sensor module using SPI communication and ensures that the module is sampled at accurate and repeatable intervals. The extracted data are then saved on an internal memory drive for later post-processing analyses by the medical team.

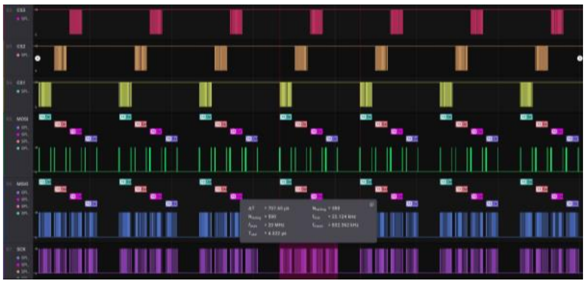

Figure 8. ADC readings in 1 kHz task

The real-time controller monitors the active elements of the system and collects telemetry. Telemetry is exchanged between the real-time controller and the high-level software over UART. The timestamped data from the real-time controller is read by the high-level controller and stored in the exercise database tagged with the information necessary to reconstruct the individual exercise sessions.

For higher level control of the NEX4EX exercises and protocols, the communication channel is used by the OBC to configure the actuators for the present task and monitor the overall configuration of the system. Once the high-level controller is satisfied that the system is correctly configured it triggers the start of the exercise. The data from the real-time controller is monitored to measure exercise progress.

3.6. SAFETY AND STATE MACHINE

A single hardware STO line connects all the motor controllers to the internal safety board and the external enabling devices.
Each of the motor controllers used on the postural modules is connected to the global STO system line. If, for any reason, the STO line is cut (open circuit), all of the motor controllers will be disabled preventing any mechanical power from reaching the user. This behaviour is fully controlled by hardware electrical elements and never relies on software control.
In addition, the system maintains a high level physical model of the system to estimate the force stored in the system and the force transmitted to the user. The goal is to ensure that the total energy stored in the system or transmitted to the user remains under a pre-defined safe threshold.
Should the physical model indicate that this is no longer true, the safety line will be triggered to bring the device back into a safe state. The state of the system will be communicated to the subject via the HMI.

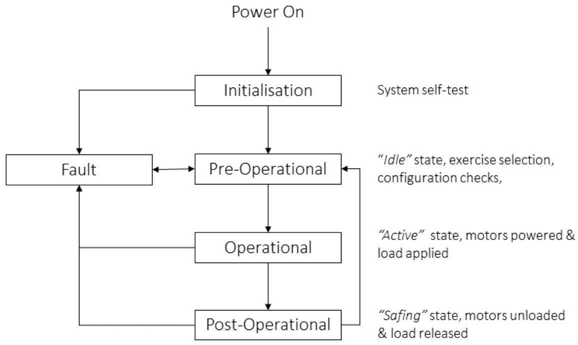

Figure 9. State machine describing the activation sequence of the NEX4EX exerciser.

In combination with the physical model, the Main Controller implements a state machine to enable and manage the control of the exerciser (see fig. 9). The transition from one state to another is based on the checking of specific parameters and measurements variables (e.g. pressing the emergency switch makes the system to go to the Error state). The status information is used internally to the Main Controller.

3.7. GROUND SUPPORT EQUIPEMENT

The MGSE frame has been designed to minimize the effects of the Earth's gravity during the ground clinical tests. The MGSE is adapted between each tests and exercises to better support each specificity of the motion.

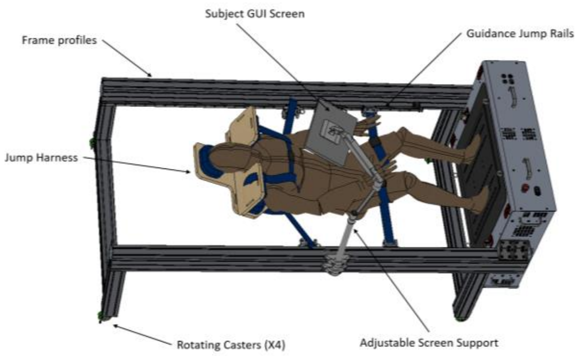

Figure 10. Horizontal MGSE frame

The tests for plyometric and squatting exercises will use the horizontal jump bed frame presented in Fig. 10. The sensorimotor exercises will use a vertical weight support harness.

4. MUSCULO-SKELETAL SIMULATIONS

The design process of the NEX4EX device has been supported by inverse dynamics simulation of a realistic model of a full-body muscular-skeletal system. We highlighted the ability of the exerciser to generate the proper muscular response from forefoot hops and countermovement jumps.

Musculoskeletal simulations using the AnyBody Modelling System has been performed on the high intensity and high impact load exercises to ensure that there are no critical internal body loads on the human subject as part of the safety analysis. Additional simulations have been done to compare the loads in the exerciser with similar exercises in gravity, to support the efficiency evaluation. The two simulations are presented in Fig. 11.

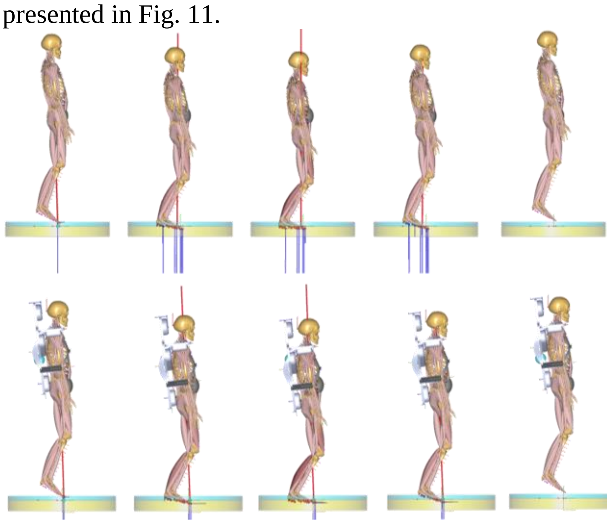

Figure 11. Motion pictures of forefoot hopping (landing-take-off). Top: Baseline model, Bottom: NEX4EX

The results display a relative comparison between a baseline model and the NEX4EX model, both models being governed by the same simulation assumptions. The relative comparison to evaluate the efficiency of the NEX4EX shows that the forces and moments in the tibia and femur are comparable.

5. FUNCTIONAL TESTING AND SCIENTIFIC EVALUATION

We are currently finalizing the functional testing and starting a scientific evaluation campaign to validate the main functions of the system. Successful performance of the postural sensorimotor and plyometric exercises, including the measurements of relevant biomechanical and electrophysiological parameters, would validate that the NEX4EX exerciser fulfils the technical objectives for such trainings.

The initial functional testing phase has been conducted with a focus on:

- Calibrate and optimize the control parameters;
- Assess the proper functions, characteristics and performances of the sub-modules;
- Assess the proper function of the safety hardware, low-level and high level software safety features;
- Perform a preliminary usability and comfort analysis not implying loads tests on human subject.

During the clinical evaluation of the NEX4EX device at DLR, we will test with human subjects the physical performance and the acute physiological reactions of the different training modes. The focus will be on sufficiently high training stimuli, safety, reproducibility, and reliability of technical performance. Biomechanical properties and physiological reactions of the plyometric exercise on NEX4EX will be compared to conventional countermovement jumps and hopping on a platform measuring ground reaction forces.

The examination will be composed of 10 subjects (5 males and 5 females, age between 30 and 60) on 2 days each. The first day includes the medical check familiarization with the NEX4EX device, control jumps and hops, and the determination of the one-repetition maximum force for squats and heel raises on a Smith machine. On the second day, subjects perform the whole set of corresponding equivalent exercises on the NEX4EX device.

6. CONCLUSION

This paper presented the NEX4EX system as a compact and polyvalent device for applications of countermeasure for astronauts in space.

Even if the core technology selected for the current prototype is compatible with an evolution toward a flight ready device, some design elements will have to be improved and adapted for future space applications, in association with a selection of compatible training protocols.

The clinical evaluation will provide further conclusions based on the feedback from the group of tests subject and from use of external clinical measurements. It is mainly expected feedback regarding user comfort and system usability targeting user-machine interfaces, body size/force adjustment mechanisms or GUI interfaces.

7. ACKOWLEDGEMENT

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