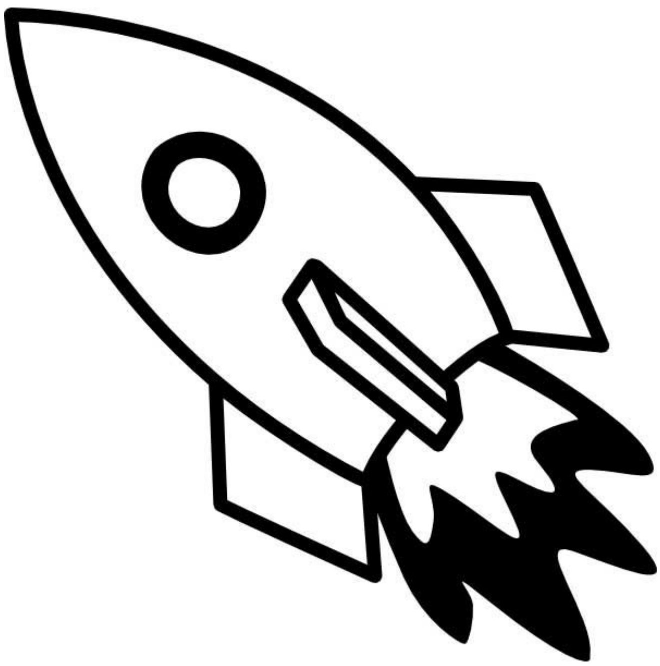
Project ExerSpace

A pre-study and State of the Art for exercise equipment in space



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Peter Fjellander	910618-0517	peterfj@kth.se
Tommy Nilsson-Hedman	881223-7553	tommynh@kth.se
Jennifer Tannfelt Wu	930416-7746	jenwu@kth.se
Dieter Henz	900531-3318	henz@kth.se
Martin Isacsson	920123-5977	isacsso@kth.se
Masoud Nadi	891226-2659	masoudn@kth.se
Hanna Hellman	910402-3347	hanhel@kth.se

Abstract

In order to maintain human physique in zero gravity, it has previously been concluded that the best countermeasure is through resistance training. Maintaining fitness in order to assure a smooth return to earth for Mars-travelers also includes aerobic training. For a journey to Mars the space in the Orion capsule will be very limited. Thus, the problem definition of this project is to research the area of combined resistance and aerobic training, and in the end to come up with a prototype that is possible to scale down in size to fulfill the tight volume and weight restrictions. This report covers a pre-study along with State of the Art research and concept development. There are some machines which can be used for capsule space flights but none of them are within the constraints of this project. They are either to big, cannot deliver a great quality of exercise or cause too much vibrations.

Contents

Nomenclature

Abbreviations

Abbreviation	Description
μG	Microgravity
ISS	International Space Station
ESA	European Space Agency
NASA	National Aeronautics and Space Administration
KI	Karolinska Institutet
M-MED	Multi Mode Exercise Device
ARED	Advanced Resistive Exercise Device
IRED	Interim Resistive Exercise Device
MR	Magneto-Rheological
VR	Virtual Reality

1 Introduction

The record for most consecutive days in space is 438 days, held by Valeri Polyakov. However, a colonization of planet Mars would entail six to seven months of traveling in a micro gravity environment. Not only would traveling in a confined space with the same people for six months be an interesting test of the human psyche and social relations, but the effects on human physiology caused by zero gravity are widely studied. Loss of bone density and muscle mass are currently some of the biggest obstacle for traveling to Mars. Solving this problem while meeting the tight requirements of the Orion capsule, which is intended to be used for the first manned mission to Mars, holds a big incentive for space agencies.

2 Background

Various countermeasures for muscle- and bone loss have been proposed, such as artificial gravity, pharmacological treatment, negative pressure on lower body and electrical stimulation (Berg and Tesch (1998)).

In Caiozzo et al. (2009), artificial gravity was examined through the use of a short-armed centrifuge on subjects put on bed rest. The results revealed, that artificial gravity was partially effective on maintaining functionality in the knee extensor and plantar flexor muscle groups.

In Smith et al. (2012), a study was performed on returning astronauts which had followed a regimen of exercise and nutritional intake during their stay on the ISS. This approach was shown to mitigate bone loss. Although a limitation of the study was that it could not be allocated which results were caused by resistance exercise and which by nutrition intake.

Physical exercise has proven to be most effective countermeasure (Berg and Tesch (1998), Alkner and Tesch (2004)). However, aerobic training will not produce these positive results - *only resistance training.* Likewise, resistance training will not have effect on endurance and stamina (Berg and Tesch (1998)).

2.1 Bone and Muscle loss in a microgravity environment

Long term spaceflight has been shown to result in loss of bone minerals (Lang et al. (2004)), mainly in the lower limbs where the major part of body weight rests on earth, while only marginally in the upper body limbs. Although the loss of bone density is less severe than the loss of muscle performance as a result of long term stay in a μG environment. Furthermore, the bones will need longer time to recover than the muscles (Berg and Tesch (1998)). As a general rule of thumb it can be assumed, that, without countermeasures, muscle volume of load bearing muscles will decrease by $2-3\%$ per week and muscle strength even by 5% per week (Alkner et al. (2003)) as a result of unloading in a μG environment.

2.2 Studies on subjects after space flight

Studies on crew members of the ISS have been performed, for example in Lang et al. (2004), where 14 astronauts were examined pre- and post-spaceflight through scanning of the hip, lumbar spine, and heel (Lang et al. (2004)). It showed, that subjects lost an average of 1% of bone mineral per month which was deemed coherent with earlier studies. The conclusion is that an aerobic exercise regimen on ISS is not enough to counteract loss of bone minerals (Lang et al. (2004)).

2.3 Studies on earth (Bed rest studies)

Bed rest studies are used to simulate a μG-like environment for the human body on earth. This is used to look into the impact on the body's muscles and bones. Study subjects will rest in bed with a 6° head-down-tilt. During a 110 days bed-rest study, Alkner et al. gave the subjects an exercise schedule, which consisted of an altering 2-3 resistance workouts per week including the following exercises: calf raise, squat, back extension, seated row, lateral shoulder raise and biceps curl. All exercises were realized on the flywheel, known as M-MED (Multi Mode Exercise Device) from *YoYo*

Technology AB, Stockholm, Sweden (Alkner et al. (2003)). The study revealed that it is possible to completely eliminate muscle atrophy in load bearing muscles with this exercise schedule. Moreover, the subjects could gain strength during the 110 days (Alkner et al. (2003)). During a shorter bed-rest study, Alkner and Tesch showed, that it is possible to maintain muscle volume and strength with less frequent exercise than 2-3 times per week (Alkner and Tesch (2004)).

2.4 Combined aerobic and resistance training

A general problem for capsule flights will be to train two different kinds of fitness, since there will only be room for one training equipment on board. However, there is still the need for resistance training to prevent muscle atrophy and also aerobic training to maintain blood circulation system physiology. There are very few exercise devices which can provide both kinds of exercise in one machine. One is the previously mentioned M-MED which was able to raise the muscle strength and aerobic capacity of the test group. This was proved during a 5 week study with 3 aerobic and 2 resistance exercises a week. However, the effects were only proven on subjects, which have not exercised at least six months prior to the study. It is still unclear if this holds also for well trained astronauts (Owerkowicz et al. (2016)).

3 Requirements

The need for physical exercise was already elaborated in section 2. So far the requirements have not been specified to a detailed level. This will be done in parallel with the concept development during the next phase of the project. The overall goal can be summarised as follows:

Design a concept, which enables astronauts to maintain their muscle strength, bone density and aerobic fitness in a space capsule, flying to Mars. The necessary exercises are; Squats, Dead lift and Heel raises, as demonstrated in Figure 1.

Furthermore, according to Hans Berg MD. rowing is the most suitable exercise for aerobic training in space. This project will focus on quality of exercise and proof that the concept is working.

Since there are already devices existing which could deliver these exercises, the main requirement is instead to maximize the quality of exercise. Albeit the final goal is to prove a concept, there are several other space flight related constrains to bear in mind, e.g. restriction for production of particles or redundancy electronics. The chosen concept should be able to be developed further in order to make the final device space flight compliant. In addition to that, there are further constrains, since the device will be used in a capsule, where space and load capacity is limited. Additionally energy supply is limited, so the energy consumption should be narrowed down to a minimum if not completely eliminated (energy autarkic).

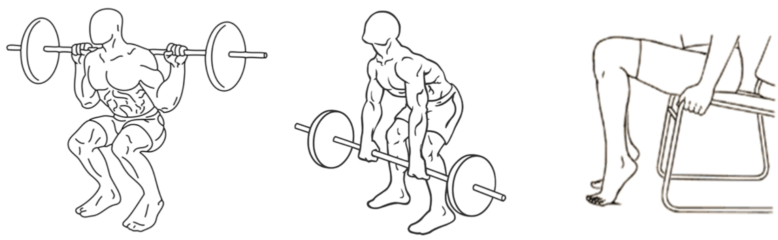

Figure 1: The three mandatory exercises, a) Squats, b) Dead lift and c) Heel raise

4 Method

The method for collecting the information used in the State of the Art was in much the same fashion as during a systematic review. A number of search-terms were devised and entered into a total of four relevant databases. From the initial results a first screening and selection was done by examining the titles of each result. From the first selection another selection was done based on the abstract of the remaining articles. Finally, a full read of the articles left was pursued to choose the ones most relevant for the topic. One of the searches is presented below in figure 2.

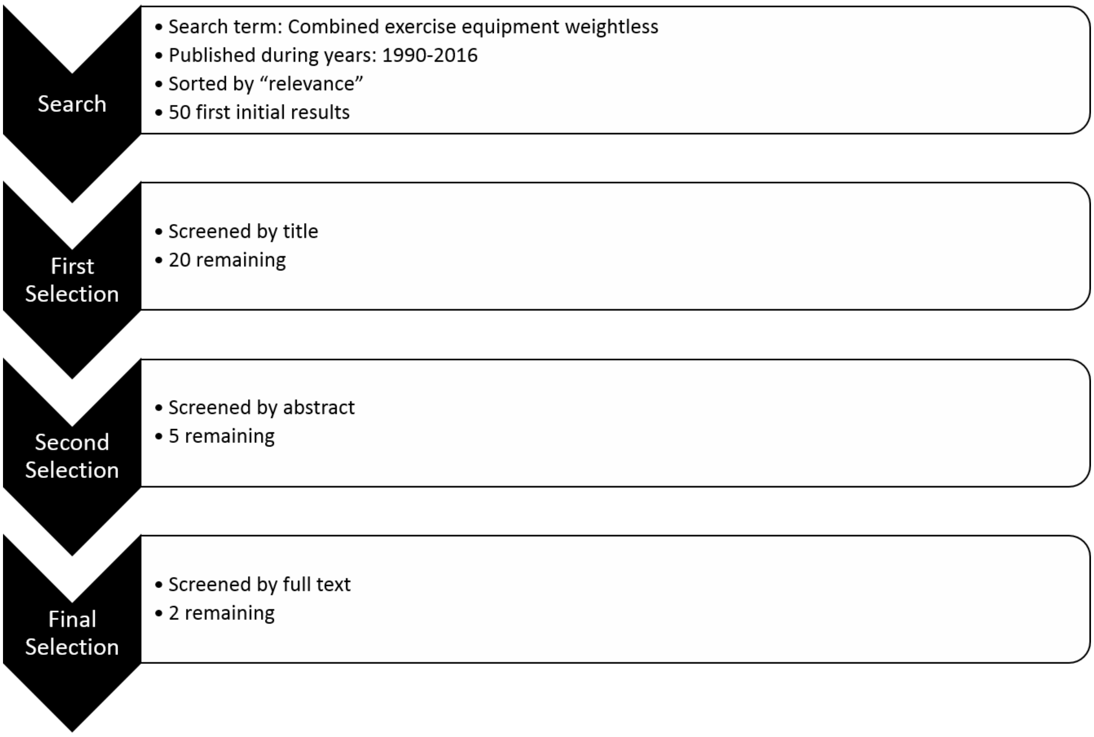

Figure 2: Example of selection performed from initial search term

Following the selection process, an extraction template (see Appendix A: SOTA matrix) was used to make sure to maintain a constant level of information extraction between both articles and participants.

5 State of the Art

In this section, the current state of the art in combined resistance and aerobic training is presented.

5.1 Exercise equipment used on earth

The project as such will have an emphasis on products developed specifically for working in microgravity. However, as there is a multitude of products available for use on earth a separate category was made to collect solutions from this field which could be feasible for the project.

5.1.1 Flywheel

A flywheel-based exercise device combining strength and aerobic training while playing video games at the same time to make the exercise more entertaining. The car in the video game moves faster as the user pedals faster and also the direction of the car can be controlled as the user pedals, as shown in figure 3. The exercise device is mainly aimed at people in wheelchairs where it is possible to mount and dismount the machine from your wheelchair. The device can be modified for use in zero gravity. The device uses a flywheel which can be adjusted for both strength and aerobic training (Guo et al. (2006)).

Figure 3: Test subject exercising at the same time as playing video game

5.1.2 Springs

A common force generator for many different applications is the spring. Spring loaded training machines have proven to be effective on earth when incorporated as an easy solution for the home gym industry (Henning et al. (2013)). Springs, however, suffer from non-linearity (Young and Freedman (2013)) which decreases the quality of exercise and reduces the range of force possible to generate.

5.1.3 Electrical

There is a vast supply of training equipment aiming for rehabilitation of patients. An arm bike showed in figure 4, as it was developed by Jeong and Finkelstein, was created for training of upper body limbs. It is also possible to use it for normal training purposes, but the actual intent is medical rehabilitation. The resistance of the arm bike can be set in the machine and acceleration sensors can monitor the pedaling speed. The sensors are connected to a computer via Bluetooth. The computer calculates the speed, burned calories in real time and counts the time and displays the data on a screen. The idea of this prototype was, that a doctor can set the optimal training for a patient (it can also be used for the ground team to set the training for the astronauts), which he/she can then perform individually without supervision of medical staff. The patient starts training and the computer is supervising the training.

Figure 4: iBike for training of upper extremities

For thigh training, there is a machine from Moughamir et al., as it can be seen in figure 5. In this machine, the user is strapped to a chair with his body and legs. The foot is strapped to the lever, which is movable and controlled by an electric motor. It is possible to set the lever motion to constant speed, constant position or constant force. The resistance is controlled with an electric motor. Depending on which training is chosen either position, speed or force will be kept constant by the implemented controller during both concentric and eccentric movement of the leg. It was discovered, that even trained athletes (sports students) were able to increase their thigh strength within 3 weeks (Moughamir et al. (2001)).

Another machine for training of thighs was developed by Moromugi et al. and is shown in figure 6. The user sits on a movable chair with his/her feet pushing against a platform. The resistance of sliding can be adjusted manually at the connected computer. There are force sensors at the feet platform, which detect the stepping force. This is used to control the sliding resistance of the chair. Other sensors are strapped around the users thigh and track the muscle contraction. The resistance of the chair movement is controlled with an electric motor. Benefit of using contraction sensors is, that the training load can be adjusted in real time to the users individual needs (Moromugi et al. (2006)).

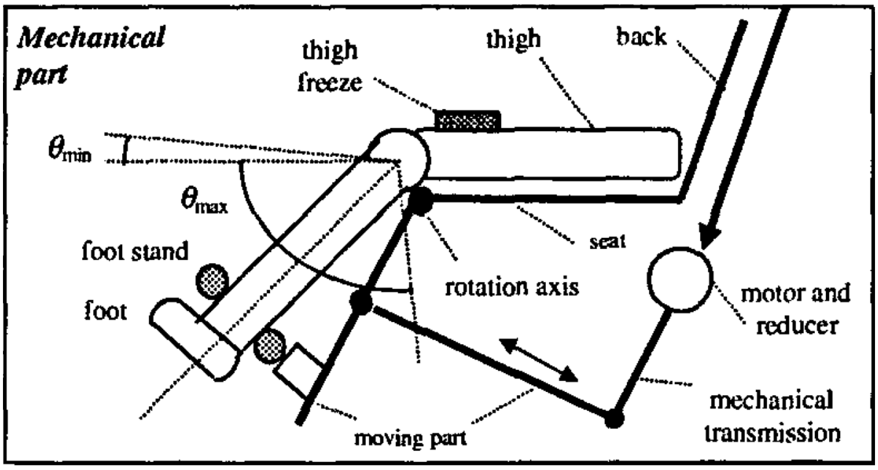

Figure 5: Training machine for thighs

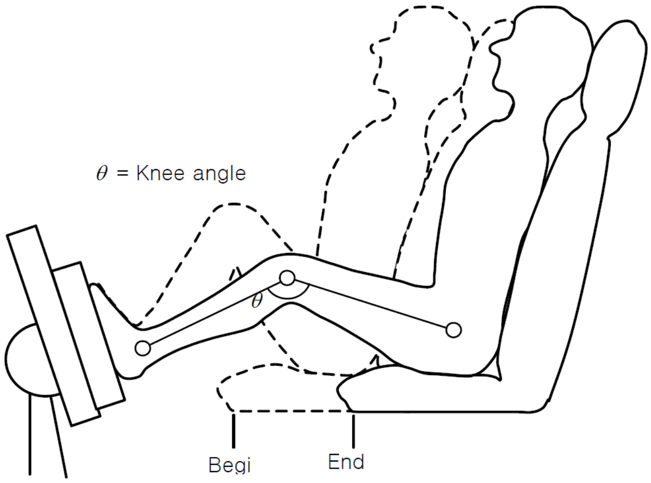

Figure 6: Training machine for lower limbs

5.1.4 Air

The main principle of the training device in article Clement and Traon (2009) is the use of pneumatically controlled rubber muscles which can by inflation/deflation give different force and torque on a users arm. Intended to be used in rehabilitation medicine for patients with a contracted elbow joint, the user's device mirrors the trainers device.

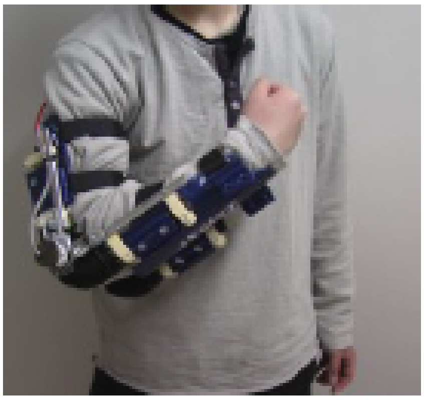

Figure 7: Prototype of device using pneumatically controlled rubber muscles

It uses two types of rubber muscles, a straight McKibben rubber muscle and a curved rubber muscle. Both are pneumatically controlled to give the desired motion of the mechanical structure which is shown in Figure 7. The device requires external power to function.

5.2 Exercise equipment used in microgravity

A number of exercise machines and different methods to prevent muscle and bone loss in space have been used in space or simulated microgravity. A selection of these machines are presented under different categories in this section.

In an article commenting on exercise devices in zero gravity (Carpinelli (2014)), the author stated IRED is one of the more promising constructions to date for maintaining muscular strength and volume. It has been appreciated to have equal effect to free-weights but had a high rate of injury, 20%. The ARED was brought up as one of the better options for resistance training. However, it has a weight of a few hundred kilograms and large. In addition it is not expressly made to account for aerobic exercise as well (Carpinelli (2014)).

The IRED has a load-capacity of 1337 N and did not provide any impressive results. While still being better than nothing it was clear that the ARED with a capacity of 1675 N and a different load-configuration produced better results as shown in figure 8 (Smith et al. (2012)).

According to the study, ARED is the only optimal exercise equipment so far that the astronauts like to use, however it is very big and requires a lot of power and will therefore be sub-optimal for a small capsule. The study concludes that few exercise equipment so far has been proven effective in space (Hargens et al. (2013)).

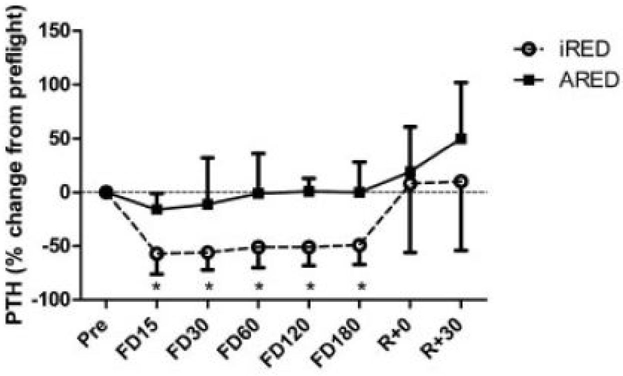

Figure 8: ARED compared with IRED, (Smith et al. (2012), fig 2)

5.2.1 Fluid

The main principle in a study by Dong et al. (2006) is actuation through Magnetorheological (MR) fluids, where the viscosity changed by varying the magnetic field around it. The knowledge that muscles can generate different torque depending on joint angle is the pre-requisite for this study, where the aim is to develop a device for rehabilitation needs. The developed device is able to deliver precisely controlled force through a user friendly interface and be easily programmable. It also collects data regarding the patients progress.

The field of MR-fluids is mostly used in vehicle suspension systems. It has been studied by NASA for use in micro gravity settings. This study is however not aimed towards exercise in microgravity.

The study claims that MR-fluids is a good choice when the device should be able to produce variable resistance and large torque, but run on low voltage.

5.2.2 Flywheel

The Flywheel Exercise Device, or FWED, was developed on the Yo-Yo principle to keep a fully mechanical system which would not have any power consumption apart from the data-logging and sensor systems. It includes a vibration damper at the end to make sure that they do not transfer to the hull of the vessel. The flywheel will be accelerated by the user in the concentric phase and decelerated during the eccentric phase. The construct also incorporates on-cord force sensor as well as a goniometer and redundant safety brakes. It places quite a bit of emphasis on the safety and uses a *dead-mans handle* so that the emergency brakes will activate should the user let go of the handle (et al (2007)).

A similar flywheel device called M-MED was tested during a visit to Karolinska Institutet. The ergonomics of the device was not satisfactory since the machine gave an uncomfortable jerk every time the flywheel changed rotational direction.

5.2.3 Electrical

A study on using an electrical stimulation contraction as exercise to increase muscle strength using electrodes placed on quadriceps and hamstring for 4 weeks. The study showed that in some cases 8% gained muscle mass (Ito et al. (2004)).

The main principle of another training device from a study (Sasaki and Noritsugu (2009)) is a so called *Hybrid* solution, where the antagonist muscle is electrically stimulated as soon as a voluntary contraction in the agonist muscle is sensed as shown in figure 9. Hybrid in this case means the combination of electrical contraction and voluntary contraction. The device consisting in principle of:

- Fitted suit
- Joint motion sensors
- Battery
- Specially designed electrode with 20 outputs and 8 inputs to control multiple muscles
- Wires
- Electrodes
- VR-system

The lower limbs of the test subjects was studied. A Virtual Reality (VR) system provided the user with simulated visual feedback and collected exercise data.

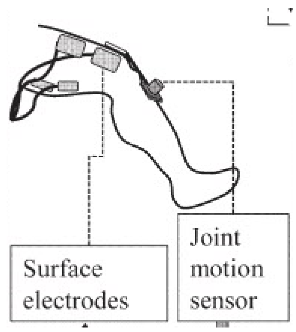

Figure 9: Placement of electrodes and sensors on test subjects

The report is a collaboration of orthopedic surgeons and control engineers. The main technology is electrical stimulation of muscles. It requires external power in the form of a battery carried on the user.

Some conclusions were that the VR-feedback improved performance in both 1G and μG. The equipment showed 20 percent increased strength in the ground tests.

A reservation regarding safety is that in μG, the range of motion of knee extension increased because of lack of gravity.

Regarding fixation to the seat and VR-feedback, fixation is necessary in the absence of VR. Likewise, fixation is not essential if VR-feedback is used. (Sasaki and Noritsugu (2009))

5.2.4 Centrifugation

To tackle the physiological problems with space flight a different solution can be found in the foundation of the problem, the lack of gravity. It has been tested several times to create an artificial gravitational force by using centrifugation. In the review article on space physiology they concluded that simulated artificial gravity while doing different kinds of exercise is the best way to keep bone density and muscles (Hargens et al. (2013)). Some of the studies on centrifugation as a countermeasure during actual and simulated microgravity are summarized in the review article Clement and Traon (2004). The generated artificial gravitational force will appear as centripetal force at the end of a rotating arm at a constant speed. An on board short arm centrifuge is presented as a realistic near-term possibility to create an artificial gravity. In this review different studies on what is the minimum threshold of gravity to be perceived by humans, how long the intervals of exposure to gravity needs to be to have an effect on humans and how often this should be repeated. These studies have been performed in different environments such as space and bed rest.

On a short armed centrifuge, the subject is generally lying on his/her back with the head towards the center of rotation as seen in figure 10. This results in a gradient of gravitational force along the body. The level of G, gravity of earth, close to the head is almost zero while at the legs the level can easily reach 2-4 G depending on the angular velocity of the rotation.

Figure 10: Schematic sketch of a short armed centrifuge

The result from a test at the Massachusetts Institute of Technology in 1997 on a short armed centrifuge indicated that 1.5 G at the feet was similar to standing, 0.5 G did not give any significant effects and a force of up to 7 G was well tolerated.

Russian scientists have performed a number of biomedical experiments during space missions' in the 1970s. Tests on animals such as ants, fish, turtles and rats where they were exposed to artificial gravity by centrifugation is one of the experiments. They were exposed to gravity of 0 G and 1 G. The results showed positive effect on musculo-skeletal systems but negative effects such as orientation disorders.

The only systematic test with artificial gravity on humans in space was performed during the space mission Neurolab in 1998. The centrifuge used was a 2-meter-long arm that could generate 0.5 G to 1 G. Four test subjects were centrifuged every second day for 45-60 minutes during the 16 days long mission. An interesting result was that just after landing, the four test subjects showed no sign of orthostatic intolerance (inability to stand upright 10 minutes) compared to all the other three crewmembers who had orthostatic intolerance. In normal cases 64% of all astronauts experience orthostatic intolerance after fights. This implies a highly positive chance of reducing the risk of orthostatic intolerance by centrifugation in space.

As stated in the background the effect on human body during long time bed rest can be compared with the effects of space flights. Some studies on the effect of artificial gravity has been performed together with bed rest. In 1998 ten test subjects were exposed to 2 G for up to 30 minutes twice a day and ten other test subjects were not. The result of this study showed positive effect on the heart rate and blood pressure for the centrifuged test group. Another similar test showed better resistance to syncope after bed rest when the centrifugation was performed during bed rest.

All these studies indicate on a positive effect from exposure to artificial gravity by centrifugation. However, a rotating centrifuge arm is not applicable to this project since it is spacious, heavy and requires a lot of energy (Clement and Traon (2004)).

5.2.5 Projects and the NASA competition

As NASA aims toward space travel beyond low earth orbit the constrains upon exercise equipment on-board space vehicles increase, which will put a limit on the equipment's volume, mass and power consumption. This is why NASA held a competition in 2015 where the challenge was to build a small and light weight exercise machine, with the requirements specified in figure 11. The resistance exercise device that won the NASA competition in 2015 used an electric motor to control the load of the machine and the maximum load it could provide was 273 kg. In order to save power, the device had a regenerative braking system (Bruinsma et al. (2015)).

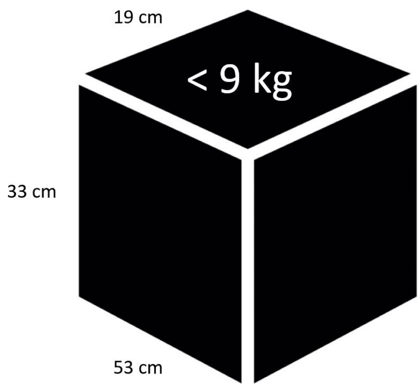

Figure 11: Requirements for the NASA competition

The flywheel has also been included as power generating device in the competition for the training device for the Orion shuttle. It incorporates both flywheel and pulleys to get the correct resistance. Due to it being purely mechanical, it only contains six steps of resistance. A drawback is the single wire to the bar which decreases training resistance. The only power used is a standard USB 500mA (Witt et al. (2015)).

Another ongoing project about a small exercise equipment was presented during the event "2016 Human research program investigators" workshop held by Genelab and the Space Biology Division of NASA. Their main focus was to provide a 2-point loading exercise device which provides good load balance when performing resistive training to increase lower body musculoskeletal strength.

They developed a pulley-based musculoskeletal loading system, built a prototype and tested it. During the test of the prototype the musculoskeletal loading system was attached to a single-cable exercises machine where the load was replaced by a flywheel. The test subjects reported a smooth movement of the cable and an evenly spread out load throughout the whole exercise. This project is still ongoing and therefore a final result is not presented. They are further developing the prototype to make it more compact and light weight. Another improvement on this project is to add the ability to measure muscle strengths during spaceflights.

5.2.6 Training harness

When training in μG, a harness is needed to reduce the load on the back due to lack of gravity. Since adding a harness may cause people to feel discomfort, quality of training is reduced (Novotny et al. (2013)). The proposed solutions have been to modify existing harnesses for training in space to fit and distribute weight like a backpacker does, approximately 30% on the shoulder and the rest on the hip. This reduces the amount of discomfort and makes training easier to accomplish. Time spending training is also reduced since no pauses recovering from harness ache are needed.

6 Result and Discussion of State of the Art

The result of state of the art showed that several attempts have been made to solve the problem of loss of bone density and muscular strength during space flights. There has been found some machines which might be considered for capsule space flights but none of them solves the problem of this project. They are either to big, cannot deliver a great quality of exercise or cause too much vibrations.

Even though there are devices existing, which could be considered for a space capsule, they still lack important key features. During a test of the M-MED at Karolinska Institutet in Stockholm, the group experienced the quality of exercise as not satisfying. Due to the wire of the flywheel is always completely unwrapped, an uncomfortable jerk is imposed on the user when changing the direction of the motion. Another flaw was that current devices induce vibration to the space capsule, which was voiced by Hans Berg, MD at Karolinska Institutet. This is also also a major problem, since it will not be possible to carry a vibration canceling system as it is present on the ISS.

These two issues will have to be tackled during the next phase of the project. It is possible to take existing equipment and further develop it towards higher quality of exercise and less vibration production.

7 Proposed design

7.1 Concepts

In order to generate different concepts, the stakeholders needs and requirements were interpreted as a set of problems to solve. The problems were broken down into simpler sub-problem such as different ways of generating braking force. Solutions were researched for each of the sub-problem. Four concepts were developed which all met the requirements and specifications.

7.1.1 Concept 1: Electrical solution

In this concept, force is generated solely by an electric motor. There is a wire wrapped around the shaft of the motor which is pulled by the user on the other side. As it can be seen in figure 12, there is a force sensor in the frame of the device, which is pushed by a lever attached to the motor. The motor itself is mounted fixed only along its rotational axis, but rotatable otherwise. A force $F_R > 1$, will be generated, when the user pulls on the string ($F_T > 1$). The value is depending on the motors torque. This alignment allows to control the motor torque, which produces the training force, through the detected force applied from the lever very precisely.

To avoid the jerk, which occurs in the flywheel when the direction of the translational movement changes, the wire in this concept is never completely unwrapped. Another benefit of this concept is, that it is possible to simulate every behavior, such as flywheel, spring or air based brake. Through this it is possible to simulate a rowing machine ($F_T > 1$ when wire is unwrapped, $-1 > F_T > 0$ when wire is wrapped in) for aerobic exercises as well as a resistance machine ($F_T >> 1$ when wire is unwrapped, $-1 >> F_T$ when wire is wrapped in) for muscle exercise.

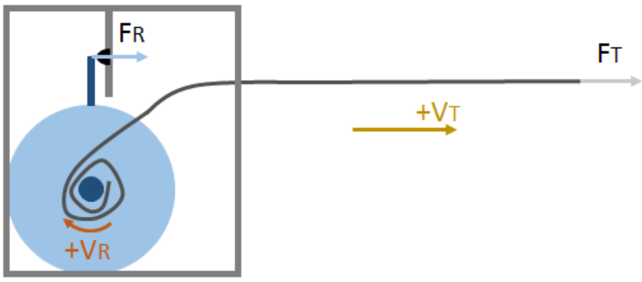

Figure 12: Concept using electrical motor only

7.1.2 Concept 2: Pneumatic solution

In order to reduce power consumption to a minimum a pneumatic solution was introduced. The idea is to use air in one or more pistons to generate force by controlling the vents which are marked by circles in Figure 13. An alternative would be to store/release compressed air using a compressor system. The exercises that could be performed with this type of concept are:

- Back extension
- Leg press

- Calf press

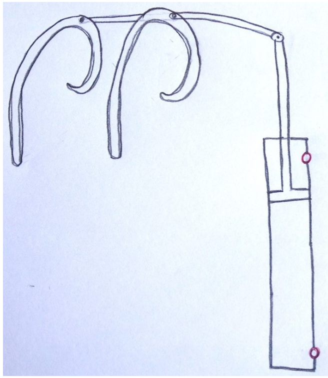

Figure 13: Sketch of pneumatic concept

Advantages of this kind of concept includes:

- Force is easily controlled by opening/closing valves
- Air is free and available, even on space stations
- Fast actuation

Whereas a disadvantage would be that the resistance will be smaller in the beginning of the movement which could introduce non-linearity to the system, thus complicating the modeling process.

7.1.3 Concept 3: Hybrid solution

As a compromise between the motor concept och the flywheel concept, a third concept was developed. It encapsulates a smaller motor and a smaller flywheel to produce the required force for exercise. You get all the pros from the electric motor, such as power regeneration while braking and the ability to simulate all types of loads. at the same time you will need less power as the flywheel inertia is producing it. The

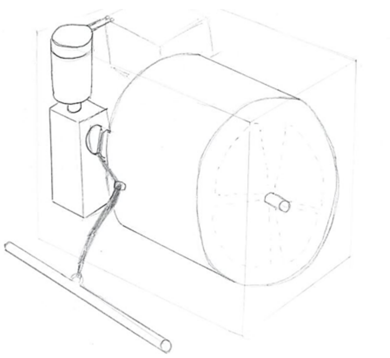

Figure 14: Sketch of combined system

concept focuses on quality of training, rather than size and weight, which will be shown during the development process. Additional complexity is added by using two main components (motor and flywheel, as seen in figure 14) for force generation. Quality of training is increase for this solution by using the motor to smooth training in the end points, i.e. when accelerating the flywheel from zero velocity. The additional complexity for this solution will generate a cost increase for every unit.

7.1.4 Concept 4: Induction braking solution

In order to reduce weight and save power the induction braking system was introduced as a concept. During research about the concept the term Eddy current brake was reoccurring which after further studying was chosen as the method to develop the concept. An Eddy current brake is a device used to brake moving object by dissipating its kinetic energy to heat. When a conductor moves in a magnetic field, the eddy currents will be induced in the conductor. These eddy currents circulate in such a way that they induce their own magnetic field with opposite polarity of the applied field, causing a braking force, as shown in figure 15. However due to the electrical resistance of the conductor, the eddy currents will dissipate into heat and the braking force will disappear (Baoquan et al. (2004)).

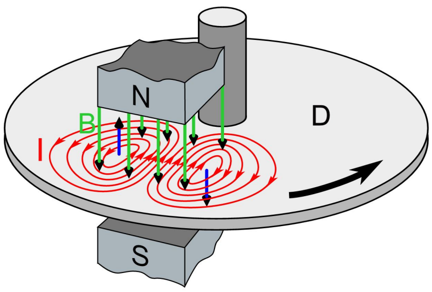

Figure 15: A metal disk rotating under a magnet, red lines indicate eddy current braking

The idea is that instead of just a flywheel we add a smaller and less heavy circular disk of conductive material which can provide the braking force needed by adjusting the current through the electromagnet to either increase or decrease the braking force, as is shown in figure 16.

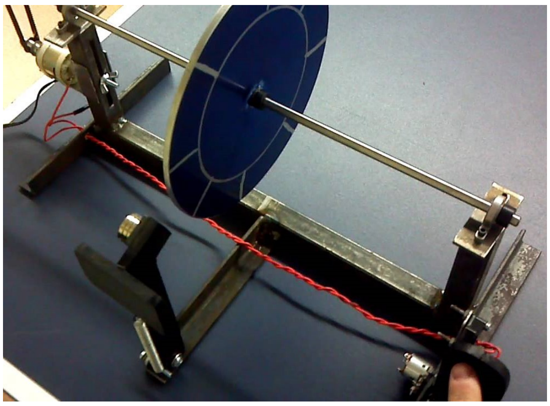

Figure 16: Braking the disk by moving the magnet close to it

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Appendix A: SOTA matrix

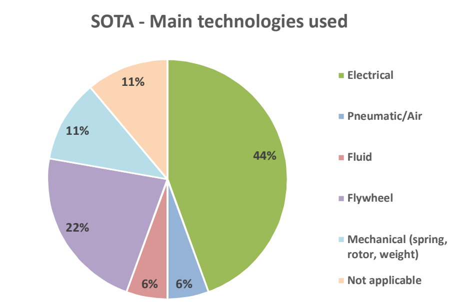
Study,Auth & Year	Study Characteristics		Exercise Device					Physiological Analysis		
	Medical/Technological	*Test Environment*	*Power Consumption*	*Size*	*Main technology/actuation*	*Ergonomics*	*Applicable in microgravity*	*Satisfactory training*	*Aerobic/Anaerobic*	*Risk of injury*
Hannas:										
Yoshimitsu et al. 2010, Training method for weightlessness, electrical and volontary muscle contraction	Both; Orthopedic surgeons and control engineers involved	1G, 2G and uG	Not stated, but requires battery	Not stated, but estimated to fit requirements (acc. to me, from pictures)	Electrical	Good, but stated that knee extension ROM increases is µG	Yes, very well so	Proven efficient under shorter periods of uG, longer periods not tested	Only **strenghtening** capacity studied. Capable of resistance on both ecc/conc movement	Over extension of knee j oint in uG conditions
D Sasaki, T Noritsugu 2009	Technical, but intended use is rehabilitational medicine	Earth, not on actual patient	Not stated, but requires power	Not stated, but estimated to fit requirements (acc. to me, from pictures)	Pneumatic/Air	Good if control system is satisfactory	Yes	Not tested within scope of study, not tested on actual patient. No muscle/training data.	Capable of both depending on controller	Stability of control system needs to be verified in order to say it is safe
Adaptive Force Regulation of Muscle Strengthening Rehabilitation Device With Magnetorheological Fluids, S. Dong et al. 2006	Technical	Earth (only on one male adult to verify control algorithm)	Yes, less than 100 W	Large, 1.2 m * 1.2 m * 1.5 m	Magnetorheological fluid actuation (fluids with varying viscosity depending on magnetic field)	Not stated, not tested on actual patients	Yes, the low-gravity environment on the ISS will eliminate the effects of sinking sedimentation. http://www.nasa.gov/mission_pages/station/research/experiments/213.html	The prototype is currently only for knee/ancle joints. The study only validated the control algorithm, not the quality of exercise.	The article focuses on resistance training but the device is deemed "flexible" and "adaptable"	No clinical trials yet.
Dieters:										
IEEE, 2012 PC assisted Training with iBikE	Medical	Test on health volunteers	not mentioned	not mentioned, but estimated: 50x50x30 cm^3	Electrical	Only for upper extremity (arm cycling)	yes	yes, as intended from medical pov no, for resistance training	aerobic	low
U Champange, 2001 Training machine for lower lims	Technological	5 sportswomen	not mentioned	huge, chair to sit and lever for quadrizeps exercise	Electrical	good	only if user is strapped to seat	yes, as intended for quadriceps no aerobic training possible	muscle (anaerobic?)	low
Effective training machine using muscle activity information U Nagasaki, Rotem, Daihen year ??	Technological	Test person	not mentioned	Huge: chair, stepping board	Electrical	Article: good But doesn't really look comfortable	only if user is strapped to seat	only resistance	muscle (anaerobic?)	low
Masouds:										
Development and Qualitative Assessment of the GAMECycle Exercise System, Songfeng Guo, 2006	Both	Earth	Not stated but requires power	Big, but foldable	Microcontroller/software, Flywheel	Very good according to test subjects	Yes	Yes, but with the lack of variations	Both aerobic and anaerobic the resistance force and be adjusted	Very safe
Development of practical and effective hybrid exercise for use in weightless environment, Tsuyoshi Ito, 2004	Mainly medical with a bit of technology	Earth	Max = 80 Volts	Very very small	Electrical	Good but depends on the frequency	Yes	The method showed a small improvement on the muscles	Mainly aerobic/slight strength training	Safe with a small risk of getting electrocuted
Novel Exercise Hardware Requirments, Development, and Selection Process for Long-Duration Spaceflight, A.S. Weaver, 2014	Technological	Earth/ISS	Less than 90 W	Max Voluem = 60.96 m^3 Weight =	Could be anything	Depends on the machine	Yes	Depends on the machine	Depends on the machine	Depends on the machine
SERVOMOTOR-BASED EXERCISE DEVICES FOR MICROGRAVITY APPLICATIONS, D.F.M. Bruinsma, 2015	Technological	Earth	Not mentioned but requires power	Not mentioned but within NASA constraints	Electrical-Servomotor	Not yet tested	Yes	Yes	Both	Not tested
Space physiology VI: exercise, artificial gravity, and countermeasure development for prolonged space flight, Alan R. Hargens, 2013	Medical	Earth/ISS	Not mentioned	Depends on the device	Electrical/Mechanical/ Artificial gravity with centrifuge	Depends on the machine	Yes	Depends on the training but resisitive training is recommended	Both	Not mentioned
Martins:										
Exercise Countermeasure to Weightlessness During Manned Spaceflight, Carpinelli 2014	Mainly technical with a medical perspective. Aims to review and comment on previous systems as described in the title.	Various, no active testing by author, evaluated objects depending on respective study	Various, no active testing by author, evaluated objects depending on respective study. None for FWED for example. Howeve artificial gravity and electrical motors all consume power	Most are rather big weighing up to 300kg which is, according to author, far more than is acceptable	Flywheel, motors, pressure, artificial gravity etc.	Overall rather poor according to author and references	All presented concepts are applicable, nearly all were specifically designed for said purpose.	Some do, however they are usually only operative within a lacking range, say for example only resistance training but not aerobic	Yes but as a rule not on the same device	Some, mainly due to poor ergonomics causing up to 25% of participants to experience back-pain depending on the device.
Upper Body Exercise: Physiology and Training Application For Human Presence In Space, Sawka & Pandoff 1991	Major focus on medical situation	Leg cycle and arm-crank exercises	None, not relevant for topic either	Not specified, focus on medical results	Rotor and weight load respectively	Assumed fair, not main focus	Likely if modified, assuming that the current machine has standard conguration using weights this has to be changed	Not main focus, Comparison between upper and lower body oxygenation effect and heat production through in relation to exercise and metabolic rate	Anaerobic	Very controlled environment assumed as medical results were the main purpose
Peters:										
Workout Machine that Combines Cardiovascular Exercise with Strength Training; A.Henning, B.Alvarez, C.Brady, J.Kopec, E.Tkacz; 2013	Technological research about the construction of a threadmill with integrated resistance training with springs	At home/ small gyms	Threadmill typical power consumption	Very large	Spring based resistance	Good	No	Yes	Both	Normal
An (Almost) No-Power Exercise Device for Orion; E. G. Witt, S. B. Tarver, and J. W. Chastain;2015	Technological research of the construction of training equipment for the orion shuttle	In space	Only USB power for sensoring	Orion requirements	Flywheel	Somewhat questionable	Yes	Hard to keep the balance with only one wire	Both	Slightly highed than normal

A harness for enhanced comfort and loading during treadmill exercise in space; SaraC.Novotny, GailP.Perusek, AndreaJ.Rice, BryanA.Comstock, Aasthaa Bansal, PeterR.Cavanagh	Medical research about harness comfort for putting bodyweight load on body in space	The Cleveland Clinic Zero Gravity Locomotion Simulator	Power for driving pneumatic subject load device	Small (just a harness)	Just about the harness	Better than before. Mild pain.	Yes	Only the aerobic part	Aerobic	Normal
Jennifers:										
Novel Musculosceletal Loading System for Small Exercise Devices, Downs et al, 2016	Technological Pulley-based loading system	Independent development (School project received attention by NASA)	None	A bit too large but is currently bring improved	Flywheel	No problems reported because of 2 point loadings. "load spread evenly"	Designed for long durational space flights	Squats and heel raises	No aerobic	Not mentioned
Centrifugation as a Countermeasure During Actual and Simulated Microgravity; a Review. Clément, 2004	Medical, collecting and comparing data. No own research	Space, bed-rest	High	Huge	Electrical centrifuge	Not very well	Yes	No, only gravity	Depends on what you do, possible to do both	Dangerous for head. Risk of gray out (fainting)

Summary of main technologies used

Electrical	8
Pneumatic/Air	1
Fluid	1
Flywheel	4
Mechanical (spring, rotor, weight)	2
Not applicable	2

Sum	18



Main technologies in articles of the State-of-the-Art analysis of 18 scientific articles. The articles have been found through systematic search of specific search words in databases.