IAC-20-D1.1.2

A Pragmatic Approach to Artificial Gravity: Testbed for Gravity Simulation Platform On-Orbit

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Abstract

This paper presents research that expands on previous investigations about a testbed for an artificial gravity platform in low Earth orbit. The initial proposal aimed to create a means for better understanding long-term effects of partial gravity on physiological and psychological human capabilities. Because human centrifuges on Earth cannot recreate effects of partial gravity on human physiology and parabolic flights fail to provide long enough exposures to generate feasible data, other research platforms to investigate partial gravity effects on humans and systems are needed. The proposed 3-body testbed comprises two customized crewed-Dragons docked to a Central Hub, which in turn docks to the Zvezda module of the International Space Station. To execute operations, the testbed will undock, retreat 2000m aft of the ISS and initiate rotation by firing its augmented thrusters. Then, the crewed-Dragons will tether out to the desired radius of rotation to begin test operations. Upon completion, the testbed will de-spin, retract its tethers and re-dock to the ISS. The sequence repeats as needed. The testbed serves two sets of test objectives: technical and physiological. The testbed's first phase will develop the technical systems to ensure the spinning testbed is human rated. The second phase will be dedicated to physiological examinations.

This paper presents the physiological experiments, their varying test parameters and subsequent recommendations for interior design features of crewed-Dragons. Crew adaptation to rotating platforms in short term, in the scale of hours and possibly days, will be the primary area of research. The paper presents three main categories of short-term physiological tests which are to assess the human body's responses to: a. Coriolis and related effects, b. Different levels of gravity, c. Different rates of angular velocity and radius of rotation. The experiments are based upon papers by James R. Lackner, Paul DiZio in 1998; Gilles Clement in 2015; and Al Globus, Theodore Hall in 2017. The parameters of the first experiment have been provisionally identified as following - a 20 min spin duration, 10 m radius of rotation, 9.5 rpm speed of rotation, 1g of gravity level. The paper presents possible subsequent experiments which allow gradual increase in time spent in a rotating environment along with variations of other parameters such as radius of rotation, speed of rotation and the gravity level generated. Finally, the paper presents interior design considerations of the crewed-Dragons. These will be based upon Theodore Hall's suggestions published in 1999.

Keywords
Crew Dragon, Testbed, Variable Gravity Research Platform, Interior layout.

Acronyms / Abbreviations

LEO:	Low Earth Orbit
AG:	Artificial Gravity
R&D:	Research and development
ISS:	International Space Station
RPM:	Revolutions per minute
TBD:	To be decided

1. Introduction

The need for additional to physical exercising countermeasures for microgravity conditions and understanding of human physiological and psychological responses to partial gravity conditions require development of new type of testbed facilities. Research suggests that artificial gravity provided with rotating structures may help to mitigate negative effects of prolonged crew exposure to 0-gravity conditions during long space flights [1]. Although it is a most common application of artificial gravity systems, there is another type of AG application for testing and evaluating human and engineering systems operations under simulated partial gravity conditions for future lunar and Mars missions.

This paper discusses implications associated with crew operations in partial and artificial gravity environments and their effects on the testbed design. A design proposal for a testbed to be in LEO and capitalize on the ISS capabilities. Major objectives of the project include minimizing time for R&D, using currently available technology, minimizing power, re-supplies and maintenance needs, and as the result – minimizing the cost of the testbed development and operations.

There is a knowledge gap in our understanding of human body's adaptation to spinning environments in microgravity and spinning environments in general [1]. Previous experiments on Earth have been captured in papers by James R. Lackner, Paul DiZio in 1998; Gilles Clement in 2015; and Al Globus, Theodore Hall in 2017. However, the experiments were confined by limiting conditions such as the Earth's gravity vector that contaminates experimental conditions, and a relatively low radius of spin due to constraints of a hosting structure.

The goal of this paper is to outline a framework that allows to perform similar experiments in LEO utilizing a testbed for a future Variable Gravity research platform. It is important to differentiate between two aspects of potential outcomes of utilization of the testbed. The first one is understanding human body's adaptation to a rotating environment and the other one is understanding a physiological response to partial gravity conditions. This testbed, due to its limited size and time for experiments will focus mainly on the first aspect.

2. Human physiological complications in rotating environment

The proposed study aims to investigate different physiological complications associated with presence inside testbed's rotating environment.

2.1 Coriolis and related effects

When a person moves radially on the floor of a rotating earth-based centrifuge, he/she will feel pushed to one side of the walls. This is how a Coriolis Effect impacts human neuro-vestibular system requiring a person to adapt to rotation in order to perform basic tasks and/or move around.

2.2 Gravity Gradient

The variation in artificial gravity level as a function of distance from the center of rotation is referred as a gravity gradient. This gradient depends on the radius of the spinning system and will decrease with increase in radius. It is important to minimize the gravity gradient because it affects a hydrostatic pressure along the longitudinal body axis. The hydrostatic pressure influences blood circulation to the head and from the lower body extremities and therefore affects cardiovascular system functionality [1].

2.3 Different rates of angular velocity and radius of rotation

We can simulate a specific amount of gravity in different ways. The radius of spin and the rate at which the spin is taking place affect the simulated level of gravity. In limited test conditions, it has been shown that with increase of the radius of spin, discomfort level lowers due to gravity gradient effects on the body. As the radius keeps on increasing, the simulated gravity will become more and more indistinguishable from the gravity we experience here on the surface of the Earth.

3. Testbed design characteristics

3.1 Testbed overview

The proposed 3-body testbed comprises two customized crewed Dragon capsules docked to a Central Hub, which in turn docks to the Zvezda module of the International Space Station as seen in the figure 1.

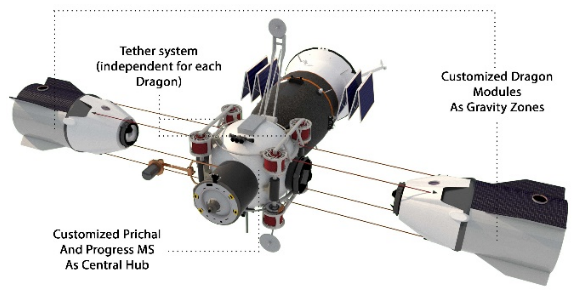

Fig. 1. The testbed and its constituent components.
Source: Authors

The testbed is a result of a phased approach towards assembly of a Variable Gravity Research platform in LEO, which will address the knowledge gap mentioned earlier. After Earth based centrifuges, the next step in this phased approach is the Testbed for the Variable Gravity Research Platform in LEO. The last step would be the Variable Gravity Research Platform in LEO itself which would allow for long term experiments. It will allow not only to test for adaptations to rotating environments but research effects of exposure to long periods of partial gravity conditions in preparation to future Lunar and Mars missions.

The testbed itself is designed to capitalize on pre-existing capabilities of the ISS and commercialization of LEO. In order to minimize time for R&D, we are proposing to use off-the-shelf technologies as much as possible including Crewed Dragons, Progress MS, and the Prichal module. As a result, it will minimize the cost of the testbed development and operations.

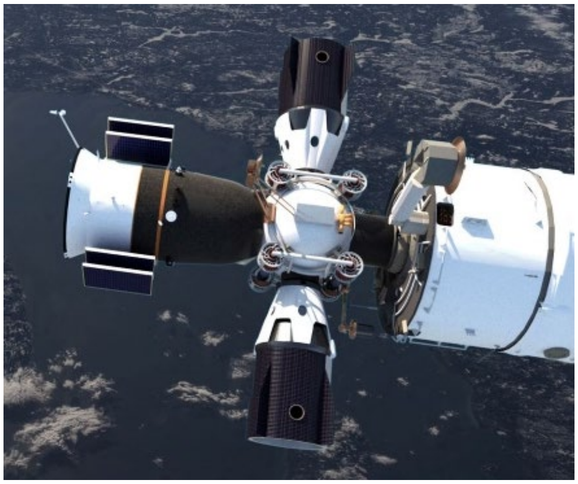

Fig. 2. Testbed docked to the Zvezda module of the ISS in its rest condition.
Source: Authors

3.1 ConOps

To execute operations, the testbed, which is docked to the Zvezda module of the ISS as seen in figure 2 will undock, retreat 2000m aft of the ISS and initiate rotation by firing its augmented thrusters. Then, crewed Dragons will tether out to the desired radius of rotation to begin test operations. Upon completion, the testbed will de-spin, retract its tethers and re-dock to the ISS. The sequence repeats as needed. The testbed serves two sets of test objectives: technical and physiological. The testbed's first phase will enable development of engineering systems to ensure the spinning testbed is human rated. The second phase will be dedicated to physiological examinations.

3.3 Test objectives

The test objectives of the testbed are divided into technical and physiological. The technical test objectives include testing sub-systems, testing docking and transfer systems and protocols, testing spin-up and spin down systems and protocols and testing structural stability and integrity. However, these technical test objectives are out of scope of this paper. This paper will focus on the physiological test objectives which include testing response to Coriolis and related forces, testing response to different levels of gravity, and testing response to different rates of angular velocity and radii.

4. Design approach / methodology

The methodology of the study included historic precedents and literature overview, analysis of experiments of preceding research of human physiology in rotating environment, analysis of anthropometrical and geometrical requirements for conducting experiments and summarizing the research outcome for proposing testbed's concept of operations. The research methodology followed the following steps:

Step 1. Identify range of motion of the human body during the experiments

Step 2. Conduct an anthropometric study to determine space required to execute experiments.

Step 3. Propose designs for interior of the crewed Dragon to accommodate execute the experiments.

4.1 Historical Precedence

After analysing various studies done primarily by NASA and ESA, we identified the most relevant experiments to the presented here proposal in Lackner and DiZio [2] study (Fig. 3).

Fig. 3. The experiment set up of the rotating room with the subject sat in the center of rotation.
Source: Lackner and Dizio

We can classify the Earth based experiments into two types based on the location of a subject in relation to the axis of rotation of the system. In the first case, the subjects are placed on the axis of rotation as shown in Figure 4 (A). This set-up is easier to produce but does not replicate the conditions we expect to see in a spinning environment in space. Since the subjects are on the axis of rotation, the apparent radius of rotation is constantly zero. Variables for this configuration include the speed of rotation, the rate of change of rotation and the duration of the rotation. This is what Lackner and DiZio adopted for their experiments.

The second case is more complex but is closer to the conditions we expect to see in space. In this case, the subjects rotate on a plane perpendicular to the axis of rotation as seen in figure 4 (B). Since the humans are placed off the axis of rotation, we introduce another variable which is the radius of rotation.

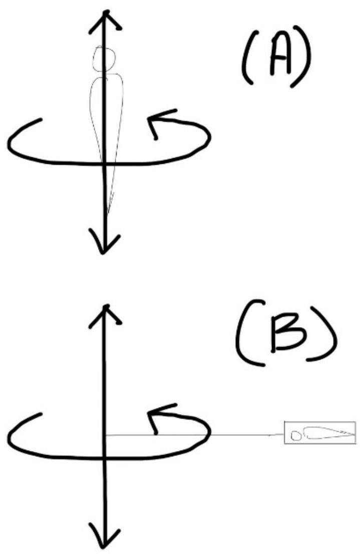

Fig. 4. A) Shows the configuration of experiments where the subject is placed on the axis of rotation B) Shows the configuration where the humans are on a plane perpendicular to the axis of rotation. Source: Authors

5. Reference experiments

The reference experiments are based on experiments done by Lackner and DiZio [2]. The intent is to study these experiments and see how we can adapt them to be executed in the testbed in LEO. In reference experiment one, we have shown how Lackner and DiZio recorded the experimental data. We can use this as a framework for recording of experimental data in the testbed in LEO too.

5.1 Reference experiment #1

5.1.1 Objective

To check for accuracy in pointing to targets.

5.1.2 Task

Extend the right hand forward to the location of a just extinguished visual target in darkness.

5.1.3 Set-up

Experiment was conducted in a dark room. When the subject lifted his/her finger from a start button to point, the target was extinguished, thus the subject reached without receiving any visual feedback about movement accuracy.

5.1.4 RPM

Not Reported

5.1.5 Duration

Not Reported

5.1.6 Note

Fingertip position was sampled at 100 Hz. The room turned counterclockwise, so forward reaching movements generated rightward Coriolis forces.

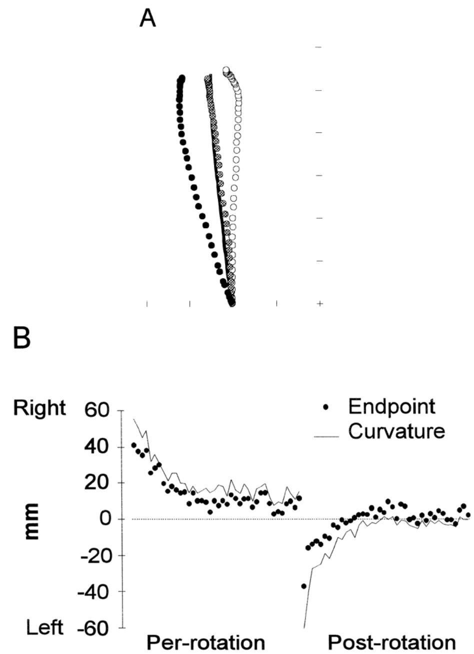

Fig. 5. A. Top view of reaching movements (averaged for 11 subjects) in the rotating room. B. Plots of endpoint and curvature with repeated movements per- and post-rotation. The horizontal axes represent average pre-rotation baseline performance.
Source: Lackner and DiZio

5.1.7 Result

Experimental data was captured in the figure 5 above. A) shows the position of the tracked object in plan. B) shows the deviation from the baseline during and after rotation. This serves as a framework for recording the data of the experiments proposed by this paper.

5.2 Reference experiment #2

5.2.1 Objective

To check whether adaptation achieved during rotation by making reaching movements with one arm would transfer to the other arm.

5.2.2 Task

Reaching movements made by one hand and then the other.

5.2.3 Set-up

Experiment was conducted in a dark room. When the subject lifted his/her finger from a start button to point, the target was extinguished, thus the subject reached without receiving any visual feedback about movement accuracy.

5.2.4 RPM

Not Reported

5.2.5 Duration

Not Reported

5.2.6 Note

Eighty movements were made with the right arm per-rotation. Post-rotation, like pre-rotation, the subject initially reached with the left arm eight times, then with the right arm eight times, and alternated in this fashion until a total of 24 movements had been made with each hand.

5.3 Reference experiment #3

5.3.1 Objective

To study the adaptation to Coriolis forces perturbations of leg movements

5.3.2 Task

Standing and kicking with the right leg at a visual target, while the head and waist were stabilized.

5.3.3 Set-up

Not reported

5.3.4 RPM

10

5.3.5 Duration

Not Reported

5.4 Reference experiment #4

5.4.1 Objective

To study adaptation to Coriolis forces perturbations of head movements

5.4.2 Task

Pitch movements of the head

5.4.3 Set-up

Not reported

5.4.4 RPM

10

5.4.5 Duration

Not reported

5.4.6 Note

A point between the eyes was tracked at 100 Hz to check the pitch, yaw and roll.

6. Proposed experiments

The proposed experiments for the testbed are based on the ground-based studies by Lackner and Dizio [2]. However, the proposed experiments can be expanded to more than this preliminary list of experiments in this paper. For example, one can imagine other experiments being done on human centrifuges to be adapted for the testbed.

6.1 Proposed experiment #1

6.1.1 Objective

To check for accuracy in pointing to targets.

6.1.2 Task

Extend the right hand forward to the location of a just extinguished visual target in darkness as seen in figure 6.

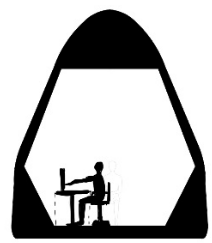

Fig. 6. Proposed experiment task of extending hand towards the screen inside the crewed Dragon. Source: Authors

6.1.3 Set-up

Lights are turned off, except for a screen showing the target. Subject is sat on a chair with arms on an armrest. When the subject lifts his/her finger from a release trigger on the armrest which also serves as a start location, the target on the screen will be extinguished. The subject attempts to place his/her finger on the recently extinguished target. Motion trackers track the fingertip location throughout this time period (@ 100 Hz).

6.1.4 Documentation of result

A plot of the position of the pointing fingertip will be gathered in top view and the deviation will be measured like the reference experiments.

6.2 Proposed experiment #2

6.2.1 Objective

To check whether adaptation achieved during rotation by making reaching movements with one arm would transfer to the other arm

6.2.2 Task

Reaching movements made by one hand and then the other as seen in figure 7.

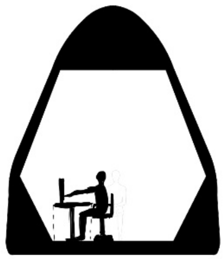

Fig. 7. Proposed experiment task of extending one hand and then the other towards the screen inside the crewed Dragon. Source: Authors

6.2.3 Set-up

Lights in the testbed are turned off, except for a screen showing the target. Subject is sat on a chair with arms on an armrest. When the subject lifts his/her finger from a release trigger on the armrest, the target on the screen will be extinguished. The subject attempts to place his/her finger on the recently extinguished target. This is intended to deprive the subject of any visual feedback about movement accuracy. Motion trackers track the fingertip location throughout this time period (@ 100 Hz). This sequence is repeated 30 times on the dominant hand first and 30 times with the other hand.

6.2.4 Documentation of result

A plot of the position of the pointing fingertip will be gathered in top view and the deviation will be measured like its reference experiment.

6.3 Proposed experiment #3

6.3.1 Objective

To study the adaptation to Coriolis forces perturbations of leg movements.

6.3.2 Task

Standing and kicking with the right leg at a visual target, while the head and waist were stabilized as seen in figure 8.

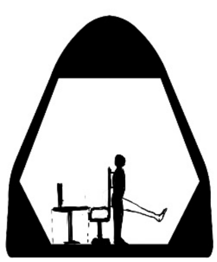

Fig. 8. Proposed experiment task of extending leg towards the screen inside the crewed Dragon. Source: Authors

6.3.3 Set-up

Subject is standing on a mark with a screen in front (and out of legs reach) and is harnessed onto a standing strap. He/she stands on a release trigger on the floor. When he/she begins the kicking motion (dominant leg) towards the target on the screen, the release trigger is released which causes the target to extinguish on the screen. He/ she attempts to kick the recently extinguished target. This is intended to deprive the subject of any visual feedback about movement accuracy. Motion trackers track the leg location throughout this time period (@ 100 Hz). This sequence is repeated 30 times.

6.3.4 Documentation of result

A plot of the position of the pointing fingertip will be gathered in top view and the deviation will be measured like the reference experiments.

6.4 Proposed experiment #4

6.4.1 Objective

To study adaptation to Coriolis forces perturbations of head movements

6.4.2 Task

Pitch movements of the head as seen in figure 9.

Fig. 9. Proposed experiment task of pitch movements of the head inside the crewed Dragon. Source: Authors

6.4.3 Set-up

Subject is sat on the chair. The subject makes pitch movements of the head. Cameras and motion trackers track the location and orientation of the head throughout this time period (@ 100 Hz).

6.4.4 Documentation of result

A 3-dimensional plot of the head pitch movements will be gathered will be measured like its reference experiment.

7. Crew Dragon Interior Layout

The crew dragon will be customized prior to purchase. During this customization, we will remove all human launch systems as humans will not be launched in this testbed. Instead most of its internal outfitting will be removed and the interior will be rendered essentially an empty space for the experiments to be performed in. Removal of all non-essential sub-systems like the Super Draco engines used for crew abort will hopefully reduce the launch and purchase cost. Thrusters to spin up and spin down the testbed will have to be incorporated into the service module of the crew dragon. However, that remains out of scope of this paper and has been teased out in a separate paper which deals with the technical test objectives of the testbed.

Figure 10 shows the estimated space we can find inside the Crew Dragon with all internal outfitting removed. Figure 11 shows a mock-up of the Crewed Dragon used for press releases. It gives us a good visual cue on the volume of space inside a Crew Dragon.

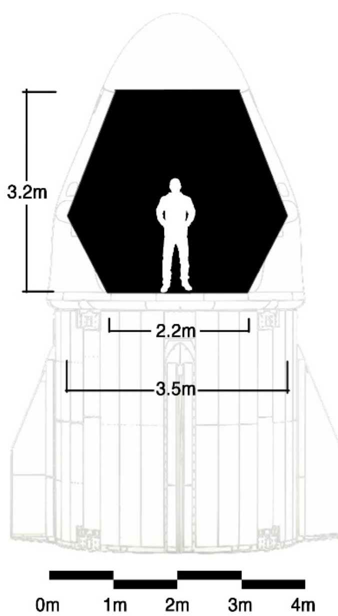

Fig. 10. Conceptual section of the crew Dragon usable volume in the testbed configuration (stripped-down as a lab)
Source: Authors

Fig. 11. Mock-up of the crewed dragon. Like the stripped-down version proposed for the testbed. All outfitting will be removed and replaced with an open plan laboratory. Autonomous launch will mean no outfitting such as seats and screens inside.
Source: SpaceX

7.1 Additional outfitting of the testbed interior

Some additional things will have to be incorporated into the interior of the crew dragon to support and enable the proposed experiment which we will go into during this section.

Figure 12 illustrates the different elements we need to incorporate into the interior layout to support the experiments. A. represents a lighting system which can be turned on and off with high precision and durability under multiple cycles of turning on and off. B. represents a video and high-fidelity motion tracking system to record the position of targets in the experimental space. C. represents a station which consists of a screen to interact with and some sort of a harness mechanism which can be a chair or a standing harness. D. represents direction markers which indicate the direction of spin of the testbed. This will come into play when we want to expand our experiments to address what Ted Hall proposes [3] which incorporates this concept of identifying the directionality of spin for the human inhabitants.

The figure 13 presents a conceptual interior layout of the customised Crew Dragon which incorporates the systems talked about above to support the experiments.

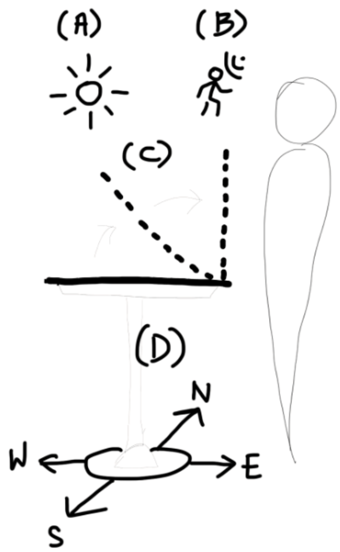

Fig. 12. A) Lights which can be turned on and off instantaneously. B) Motion tracking sensors C) A tilt-up, touch sensitive screen. D) Indication of direction of spin with interior design'
Source: Authors

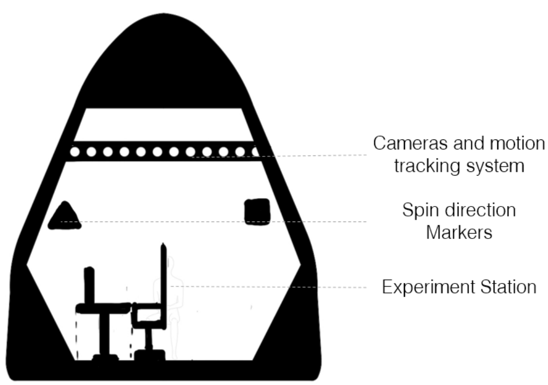

Fig. 13. Conceptual interior layout of the customized Crew Dragon outfitted for experiments.
Source: Authors

7.2 Anthropometric Study

From studying the proposed experiments to be performed inside the testbed, the following range of motions have been identified:

1. Sitting down on a chair; arms reaching out to a vertical screen
2. Standing with head and torso restrained, kicking toward a target on a screen.

An anthropometric study was carried out using the Architects data sourcebook [4] which analyzed the range of movements we can expect the test subjects to make during the experiments proposed and anticipated experiments.

The result was that for non-translational movements, as shown in figure 14 and 15, a cuboid of sides 1.75m wide, 2 m deep and 2.25 m tall would be able to fit the range of movements expected.

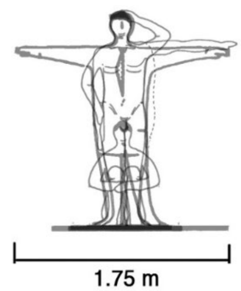

Fig. 14. Front view of movements to be performed during experiments. With a maximum width of 1.75 m.
Source: Authors, Compiled from Architect's Data by Neufert et al.

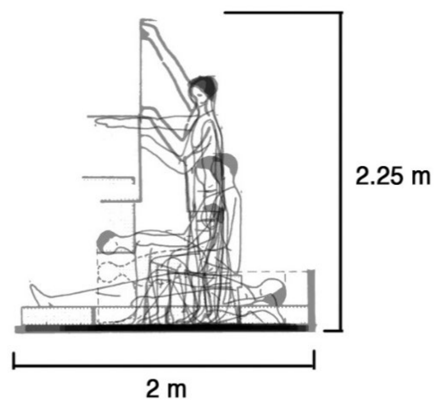

Fig. 15. Side view of movements to be performed during experiments. With a maximum width of 2 m and maximum height of 2.25 m
Source: Authors, Compiled from Architect's Data by Neufert et al.

Figures 16 and 17 below shows the anthropometric study and volume which encompasses the range of expected movements into the interior volume of the Crew Dragon.

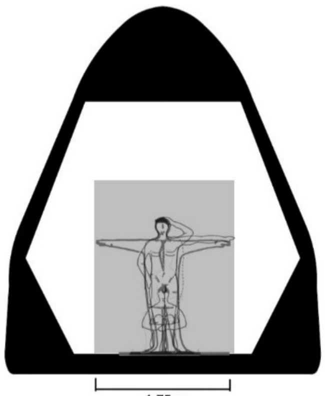

Fig. 16. Front view of the range of movements expected overlaid on the interior of a Crewed Dragon.
Source: Authors, Compiled from Architect's Data by Neufert et al.

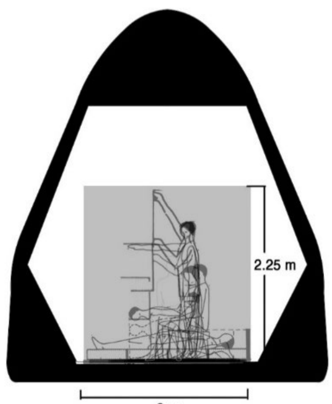

Fig. 17. Side of the range of movements expected overlaid on the interior of a Crewed Dragon.
Source: Authors, Compiled from Architect's Data by Neufert et al.

A Variable gravity environment will require variable outfitting to test for ergonomics. Although we have begun to explore what the interior layout could look like for a testbed for variable gravity research platform, the range of experiments considered and hence the range of movements here is limited. One obvious limitation is that all the movements are non-translational and happens on one spot. This is in part limited by the confined nature of the interior volume. However, we can expect to see basic translational movements like sitting up to standing up, turning around on a spot, jumping, or maybe even a few steps in any direction. And since we are aiming to induce various levels of gravity, the outfitting will need to be variable to accommodate varying configurations such as varying seating height, working table height etc. Also, the outfitting might need to be stowable to allow for multiple types of experiments.

8. Test Operations

Test operations on the testbed have been divided into two classifications. Technical and Physiological. The Technical test objectives remain outside the scope of this paper and will be executed prior to the physiological test objectives when the mission is online. Technical test operations will aim towards ensuring the testbed environment meets safety requirements and general set up of the testbed before humans are put inside the testbed.

For this paper, we will focus on the physiological test operations. They are named P1, P2, P3, ... and so on as opposed to the technical test operations which are named T1, T2, T3, … and so on. Table 1 shows how P1, and P2 might look like. They will accommodate the same experiment, ie experiment 1 but it will perform it in varying conditions. In P1, 1g is being generated with a short radius of rotation (10m) and RPM of 10. While in P2, the same amount of gravity, i.e.. 1g is being generated by spinning the testbed at a substantially lower RPM but a larger radius of spin of 100 m.

This is made possible by the tether system of the testbed. These varying levels in RPM and radius of spin will help advance our understanding of the varying levels of adaptation humans can achieve. Al Globus and Ted Hall have compiled a list of studies [5] and estimated a comfort zone with the rotational radius and angular velocity as the two variables as shown in figure 18. In it, we can see that there is no consensus on what the comfort zone is, and this testbed could be a good opportunity to test these hypotheses.

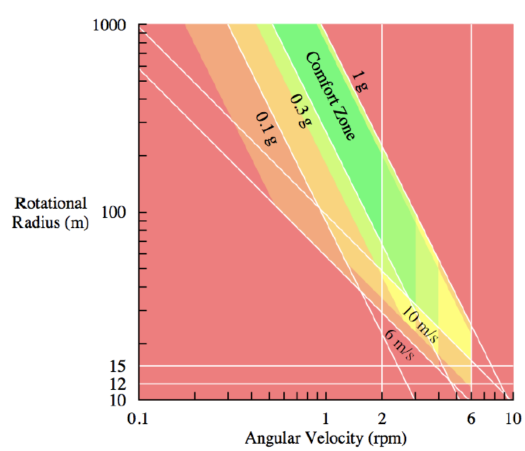

Fig. 18. Compilation of different comfort zones proposed by different studies.
Source: Al Globus, Theodore Hall.

Table 1. Sample Test operation specifications.

Test Operation ID	**P1**
Experiment ID	1
RPM	10
Radius of Spin	9.5
Gravity	1 g
Duration	20 min
Test Operation ID	**P2**
Experiment ID	1
RPM	3
Radius of Spin	100 m
Gravity	1 g
Duration	20 min
Test Operation ID	**P3**
…	…

9. Conclusion

The proposed testbed allows to estimate an adaptation period needed for humans to adjust to different operational conditions, which affects crew's productivity and functionality. Efficiency of the crew is paramount importance for mission success and the testbed offers an opportunity to gain critical knowledge about it prior to sending humans to long term crewed missions.

An important design consideration of a rotating environment is the requirement of keeping the center of mass in the center of rotation, in case of this testbed – in the central hub. One exciting implication of using a tether system with two independent lengths attached to two Crewed Dragons is that a tether's length can be varied to keep the center of mass under control to avoid eccentric spins.

This paper presents an exploratory stage of the project and in order to explore the possibilities that this testbed offers, additional research and testing will be needed. Research questions may include: can interior elements be the same for two types of test conditions (i.e. testing for adaptation to rotating environment and testing for adaptation to partial gravity environment)?

In addition, there are technical test objectives of the testbed that lie outside of the scope of this paper but have been investigated in a separate research by the authors. For example, how does air flow/fluid flow behave in the testbed during rotations? How to ensure subsystems functionality in a spinning environment? These are questions to be answered in future research.

Finally, we reiterate that the aim of this testbed is to act as a step towards closing a knowledge gap in our understanding of the human body's response to long term exposure to partial gravity conditions. At an estimated cost of about $1.5 billion, the testbed provides a low-cost opportunity to start filling this gap. Furthermore, the testbed will integrate with the ISS and take part in the commercialization of LEO.

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