Artificial Gravity Studies on Board the DSH

Artificial Gravity Study Kickoff Meeting

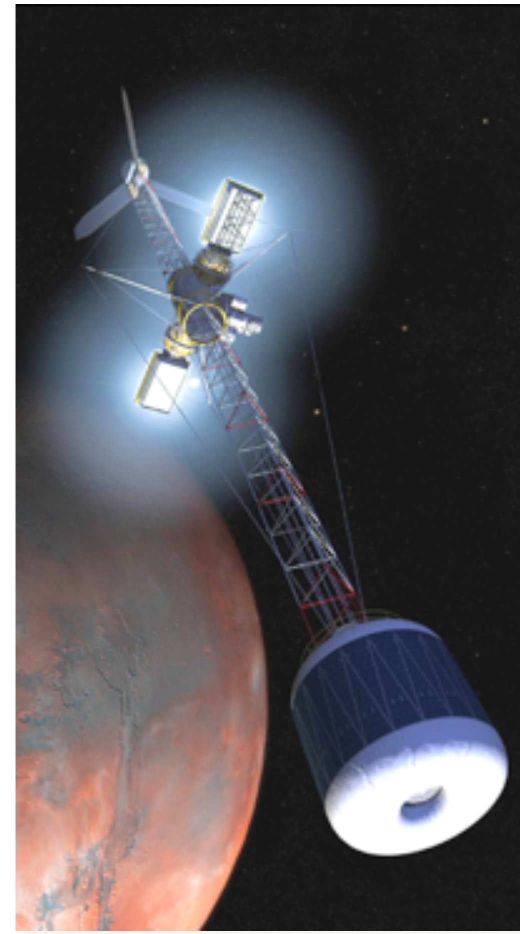
NASA Johnson Space Center
Building 15/Room 267

Gilles Clement

30 Jan 2017

Artificial Gravity (AG) Potential Benefits

- Better to prevent issues rather than to apply countermeasures after the fact.
- AG produces multi-system effects.
- AG is a potential countermeasure for VIIP (Visual Impairment Intracranial Pressure) syndrome.
- AG reduces countermeasure requirements after landing on planetary surface.
- Rehabilitation starts 6 months earlier than a non-AG mission, and is complete when crew returns to Earth.



NASA HRP – Human Risks of Spaceflight

Grouped by Hazards – 30 Risks & *2 Concerns*

Altered Gravity Level

- Vision alterations
- Renal stone formation
- Sensorimotor alterations
- Bone fracture
- Impaired performance
- Reduced aerobic capacity
- Adverse host-microorganism interactions
- Urinary retention
- Orthostatic intolerance
- Back pain
- Cardiac rhythm problems
- *Effects of medication*
- *Intervertebral disk damage*

Risks potentially minimized by artificial gravity

Radiation

- Exposure to space radiation

Distance from Earth

- Limited in-flight medical capabilities
- Toxic medications

Isolation

- Adverse cognitive or behavioral conditions
- Performance & behavioral health decrements

Hostile/Closed Environment–Spacecraft Design

- CO2 exposure
- Inadequate food/nutrition
- Inadequate human-system interaction design
- Injury from dynamic loads
- Injury during EVA
- Celestial dust exposure
- Altered immune response
- Hypobaric hypoxia
- Sleep loss & work overload
- Decompression sickness
- Toxic exposure
- Hearing loss
- Sunlight exposure

Why Has AG Never Been Implemented ?

- Lack of definitive design requirements, especially acceptable AG levels and rotation rates.
- Perception of high vehicle mass and performance penalties.
- Expectation of effective crew microgravity countermeasures.
- Space research focus on microgravity, not partial gravity.

ROCKY – Aerobic activity and strength training developed for Orion.

HRP Artificial Gravity Project

Goal

- Determine the design trade space associated with AG for Mars missions vehicles and habitats.

Objectives

- Implement an evidence-based, peer-reviewed, coordinated R&D project to investigate AG.
- Determine the optimal design characteristics for an AG countermeasure.

Milestone

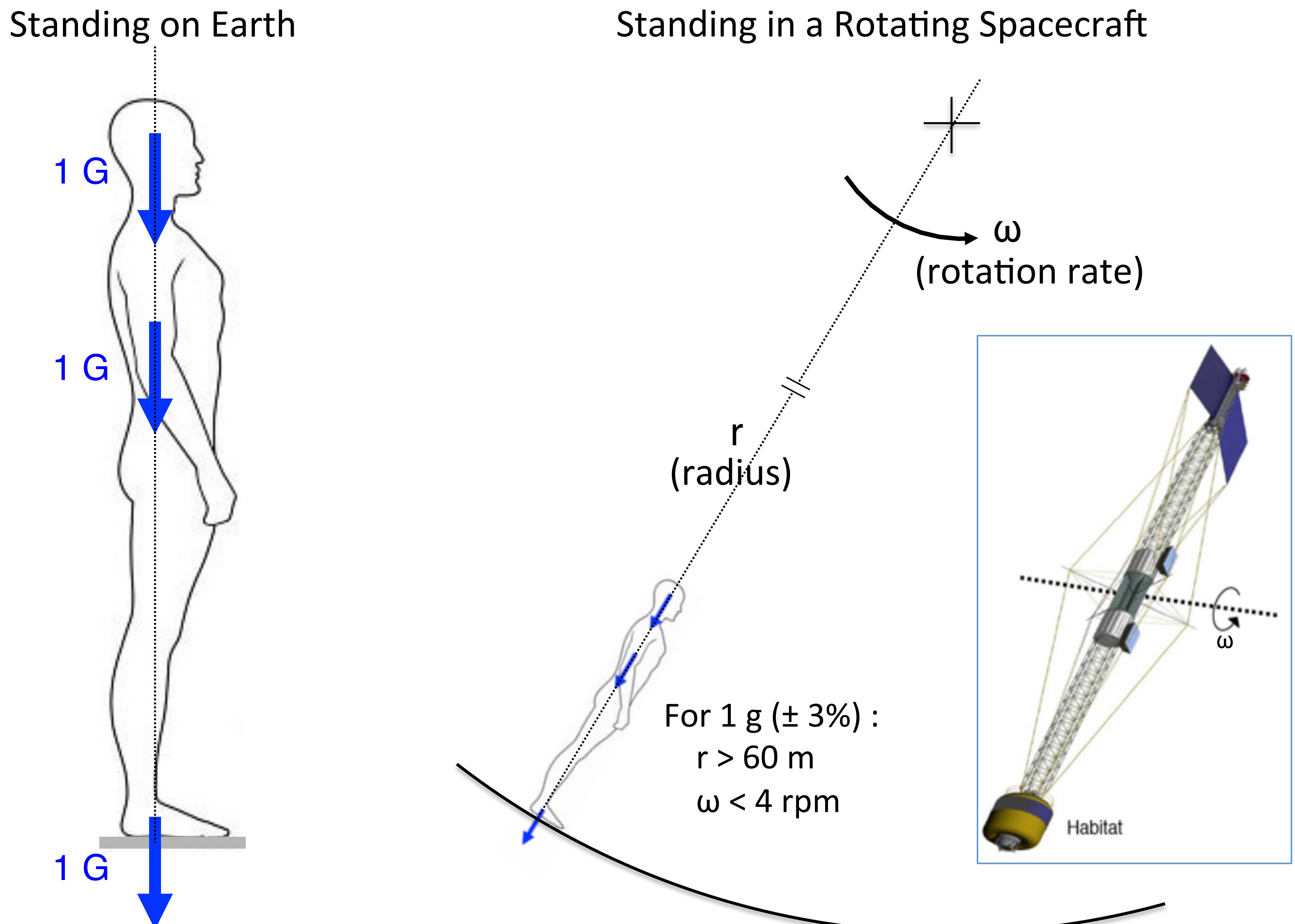
- Criteria for deciding whether AG can protect crew health and performance during human deep space missions are expected NET 2022.

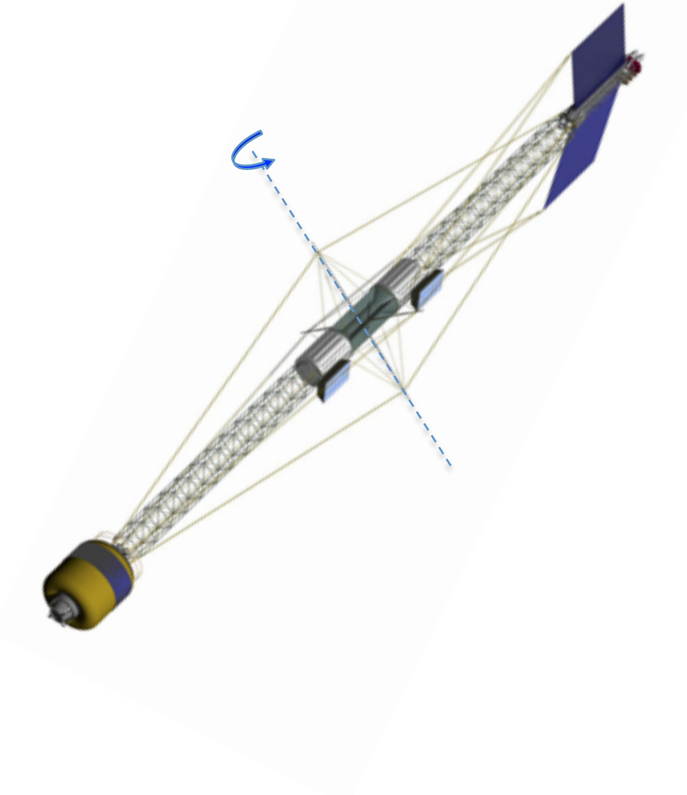
Human Health and Countermeasures Element

EM/DEM: *Baumann/Villarreal*
ES/DES: *Norsk/Barr*
ESC: *K. George*

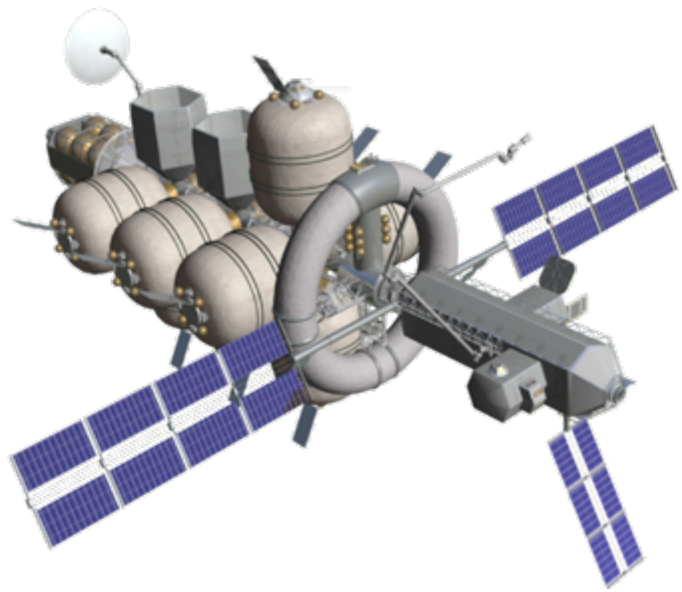
- CARDIOVASCULAR AND VISION PORTFOLIO — *Allcorn*
  - PSC : Allcorn (acting)
    - **Cardiovascular** — *Stenger/S. Lee*
      - Cardiac Rhythm Problems
      - Orthostatic Intolerance
    - Micro-Gravity Induced Visual Alterations/ICP — *Stenger/Laurie*
    - Artificial Gravity Countermeasure — *Clement*
- EXERCISE AND PERFORMANCE PORTFOLIO — *H. Paul*
  - PSC : K. George
    - **Exercise** — *Ryder/Downs*
      - Impaired perf due to reduced muscle mass, strength and endurance
      - Reduced physical perf capability due to reduced aerobic capacity
  - PSC : Taylor
    - Sensory Motor Alterations — *Bloomberg*
  - PSC: S. Smith
    - **Bone** — *Sibonga*
      - Early onset osteoporosis
      - IVD concern
- MULTISYSTEM PORTFOLIO — *Ploeger*
  - PSC: K. George
    - Inadequate Nutrition — *S. Smith/Zwart*
    - PK/PD concern — *Vacant*
    - Immune Response — *Crucian/Kunz*
    - **EVA** — *Abercromby/Norcross*
      - DCS
      - EVA Health & Performance
      - ExpAtm
  - **Advanced Food** — *Douglas*
  - **MicroHost** — *Oubre/Ott*
- TECHNOLOGY AND INFRASTRUCTURE PROJECTS PORTFOLIO — *Baumann*
  - Digital Astronaut — *Gilkey/ Lewandowski*
  - Exploration Exercise — *Haven/Perusek DeWitt/Lewandowski*
  - Translational Research — *ARC/Alwood JSC/Wu*

CROSS DISCIPLINE INTEGRATION

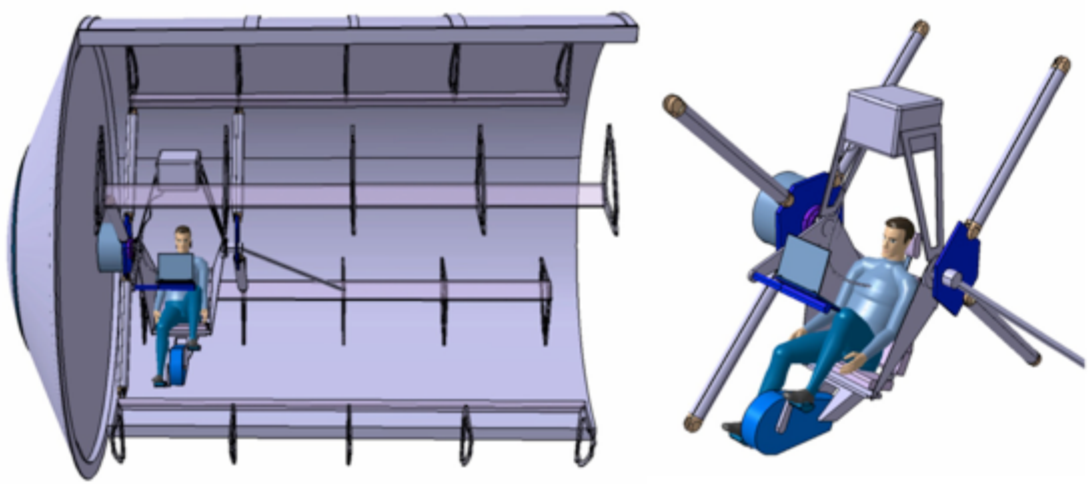

Standing on Earth
1 G
1 G
1 G
Standing in a Rotating Spacecraft
ω
(rotation rate)
r
(radius)
For 1 g (± 3%) :
r > 60 m
ω < 4 rpm
ω
Habitat



Rotation of the whole vehicle
e.g. Mars NTR
r = 56 m
ω = 4 rpm



Rotation of part of the vehicle
e.g. Nautilus-X
r = 6 m
ω = 12 rpm



Onboard centrifuge
e.g. AGREE
r = 1.6 m
ω = 42 rpm (1 g at heart)

Physics of Centrifugation

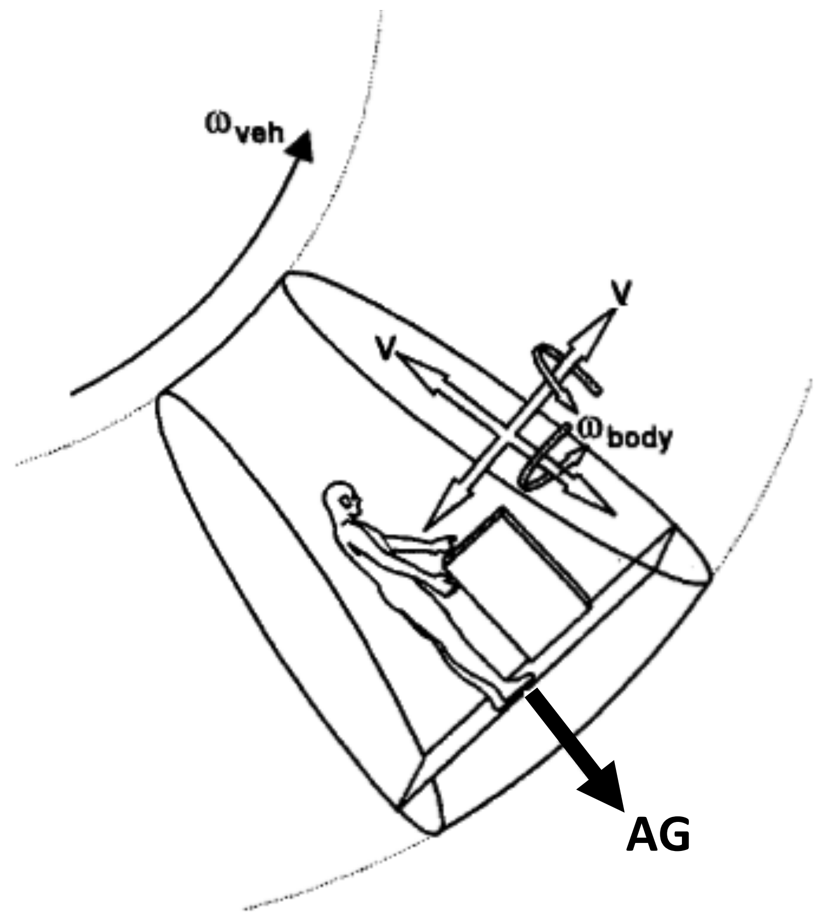
- **AG** = $(\omega_{veh})^2$ r
- Linear translation (v) of the whole body or body parts along an axis that is not parallel to the spin axis will create a **Coriolis** force:

  $-2m(\omega_{veh} v)$

- Angular movements (ω_{body}) of the head that is not parallel to the spin axis will create **cross-coupled** accelerations:

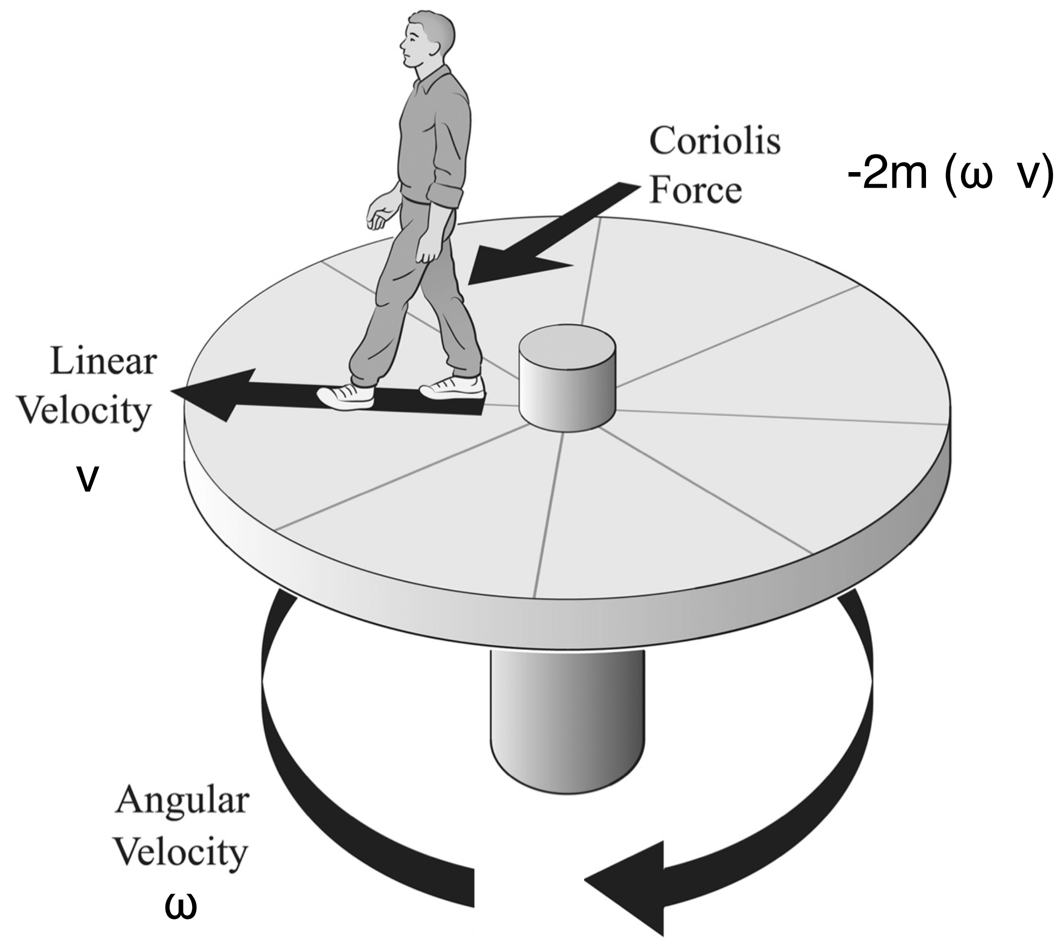
  ω_{body}

  $\omega_{veh}\cos(A)$



Lackner & Dizio (2000)

Coriolis Force – Principle



Coriolis Force during Locomotion

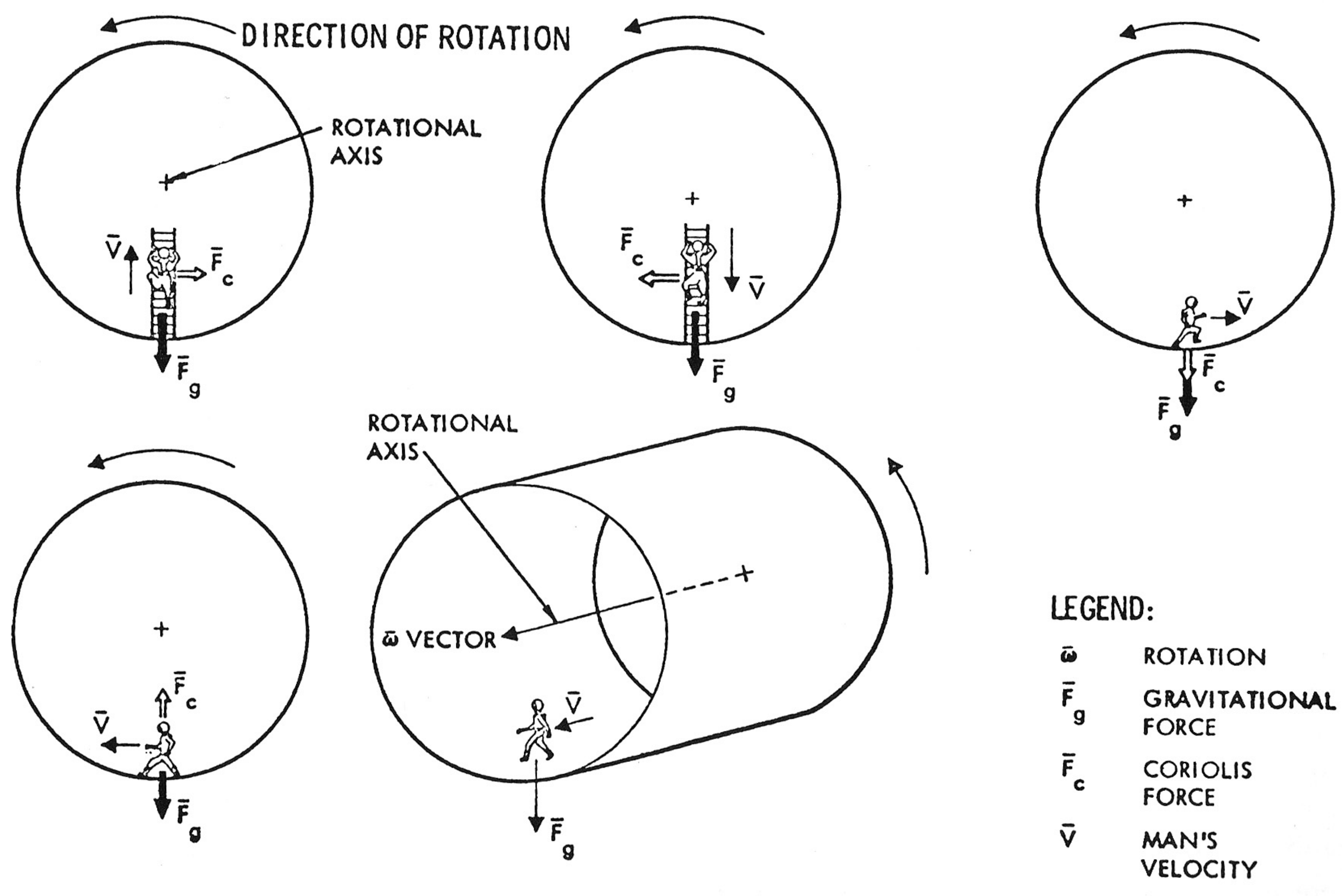
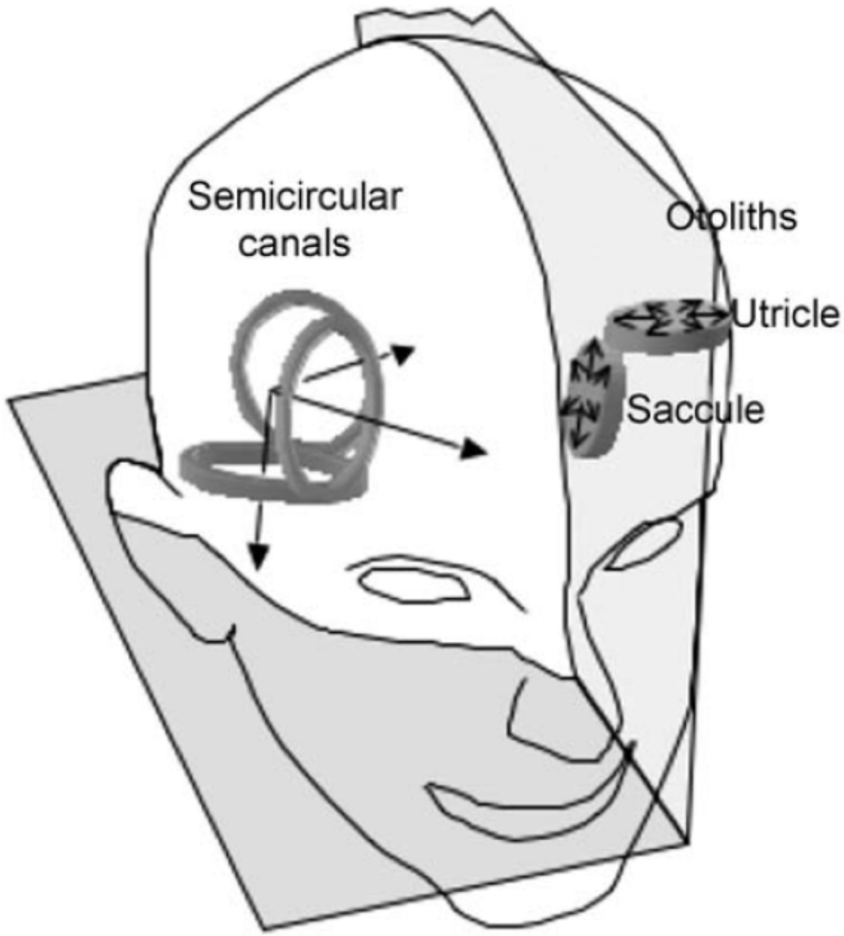


FIGURE 8.—*Influences of artificial gravity on locomotion.*

RW Stone (1973) An Overview of Artificial Gravity. NASA SP-314

Vestibular Organs

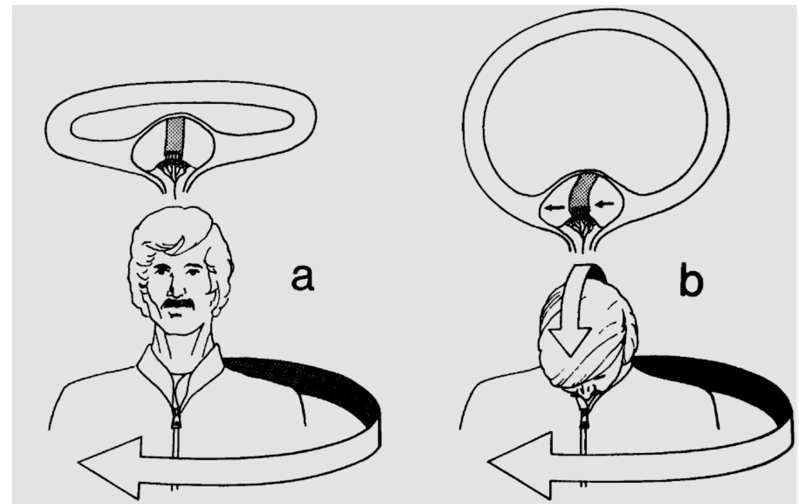


Lackner & DiZio (2005)

Cross-Coupled Angular Accelerations

When a subject tilts his head forward during passive yaw constant-velocity rotation :

- The yaw semicircular canals are brought out of the plane of rotation, and receive an angular velocity impulse.



- The pitch semicircular canals are stimulated by head pitch.
- The roll vertical semicircular canals are brought into the plane of rotation, and receive an angular velocity impulse.
- The otolith organs are stimulated by radial (centripetal) and tangential (Coriolis) linear accelerations, and signal a reorientation of the head in relation to the gravito-inertial vertical.

Cross-Coupled Angular Accelerations

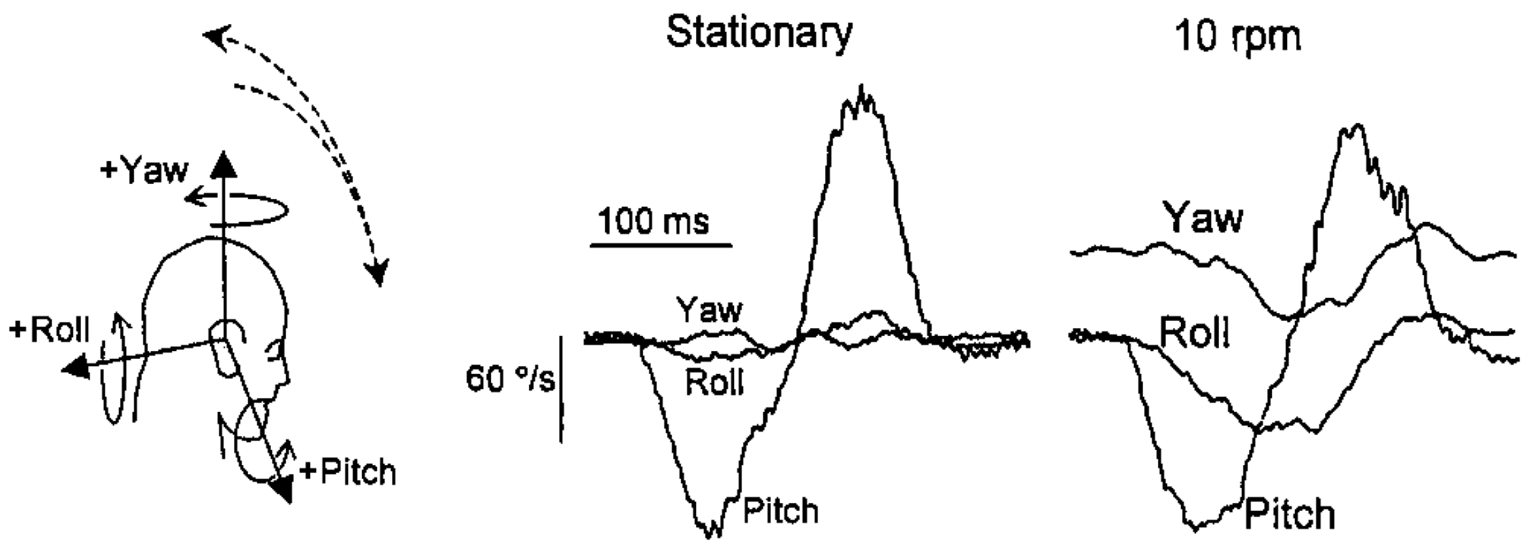
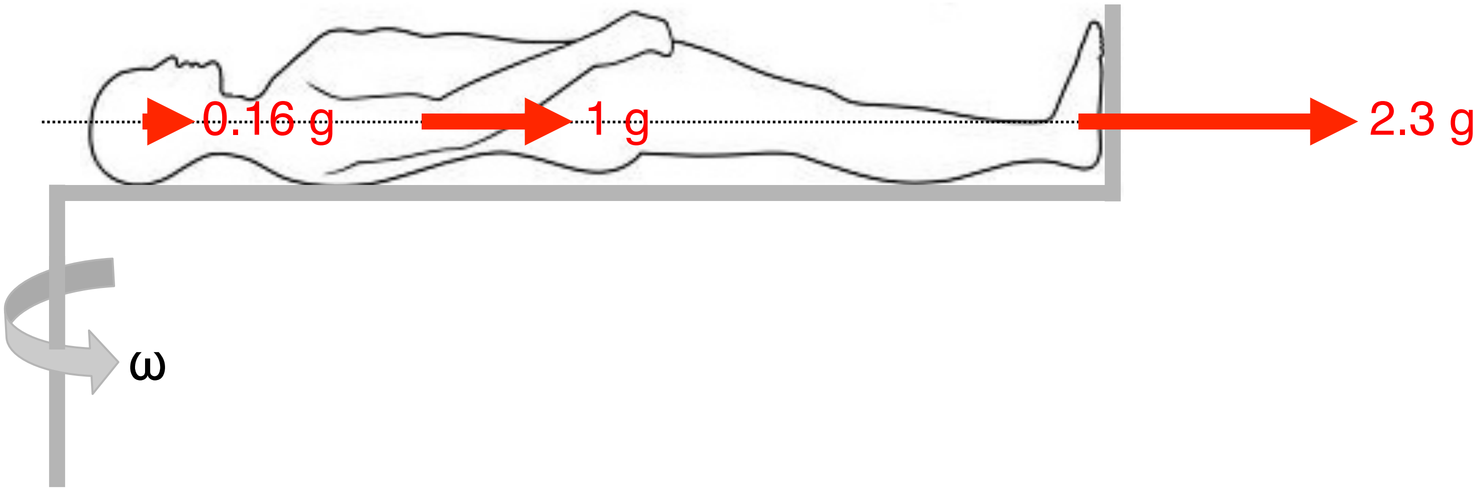
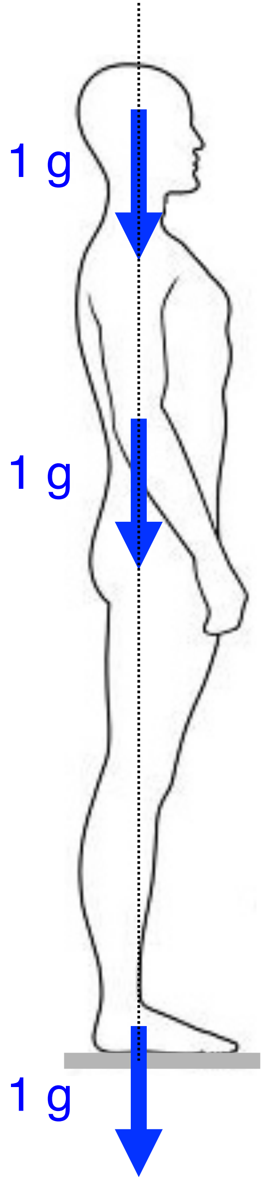


Fig. 4. **A:** Diagram showing the coordinate system of a triaxial angular rate sensor recording a movement in which the subject nods the head forward and returns immediately to the upright position (dashed arrows). **B:** Traces from the angular rate sensors when the head movement is made in a normal stationary environment. **C:** Traces recorded from a comparable pitch movement during 10 rpm counterclockwise rotation. Prior to the movement, the yaw axis of the head is rotating at the same speed as the room; pitching the head forward reduces the portion of the room rotation picked up by the yaw sensor, and returning to the upright restores it. The head roll axis sensor comes into the room rotation plane during pitch forward. The semicircular canals, which are also fixed to the head, will pick up these cross-coupled angular accelerations.

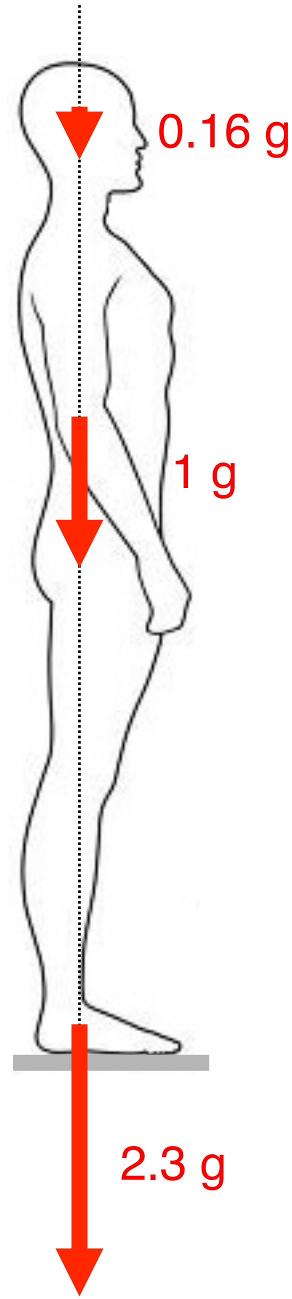
Gravity Gradient



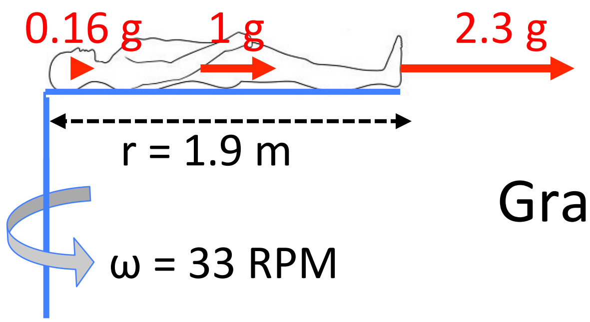
Standing on Earth



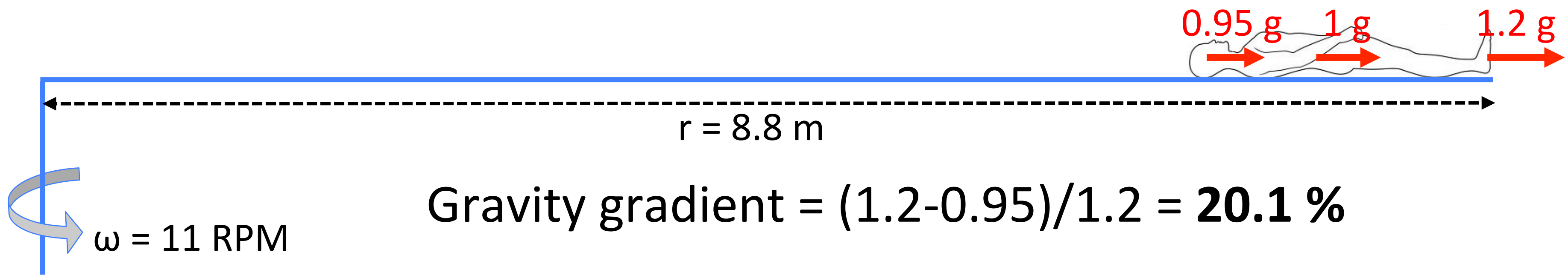
Short-Radius Centrifugation in Space



Gravity Gradient

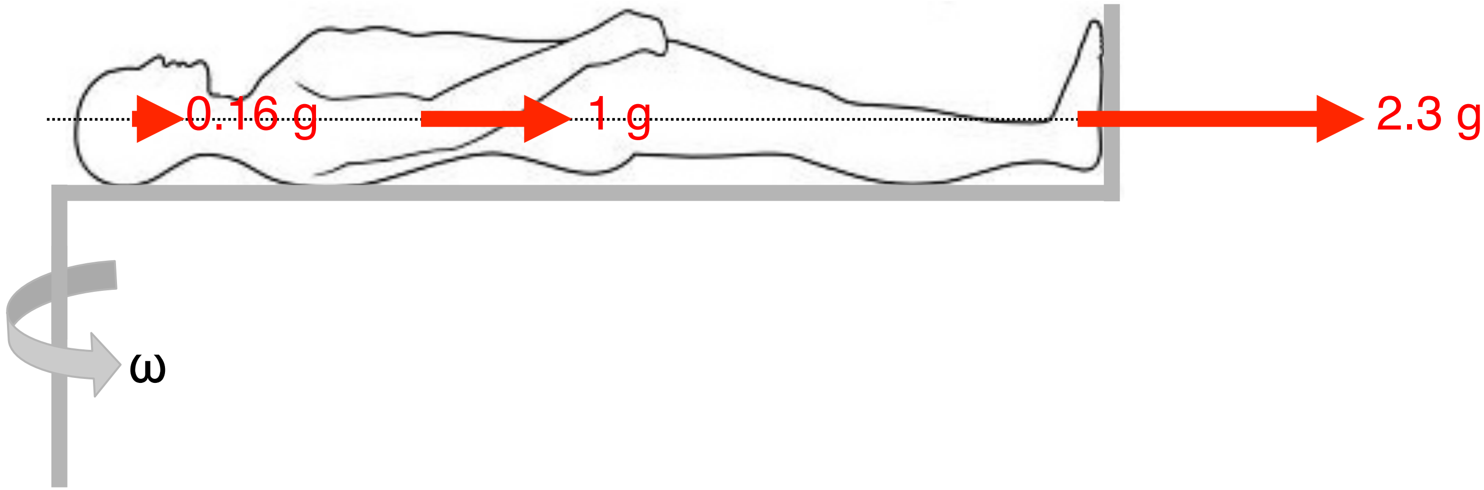


Gravity gradient = (2.3-0.16)/2.3 = **93.4 %**

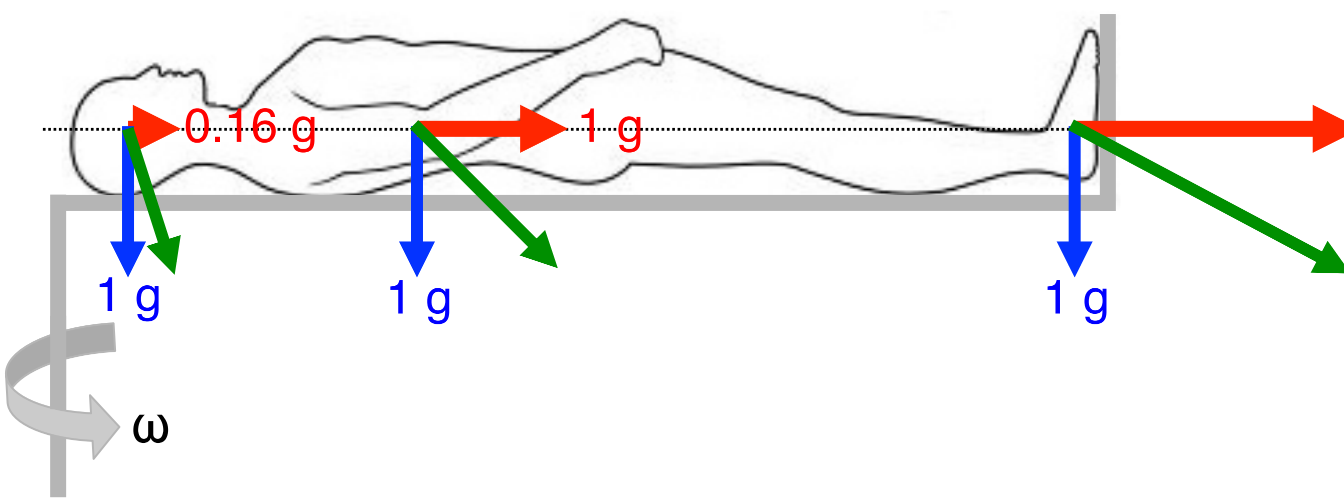


Gravity gradient = (1.2-0.95)/1.2 = **20.1 %**

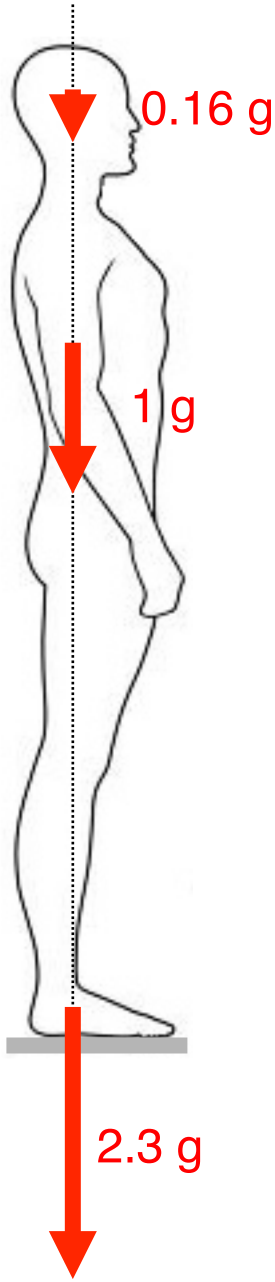
Short-Radius Centrifugation in Space



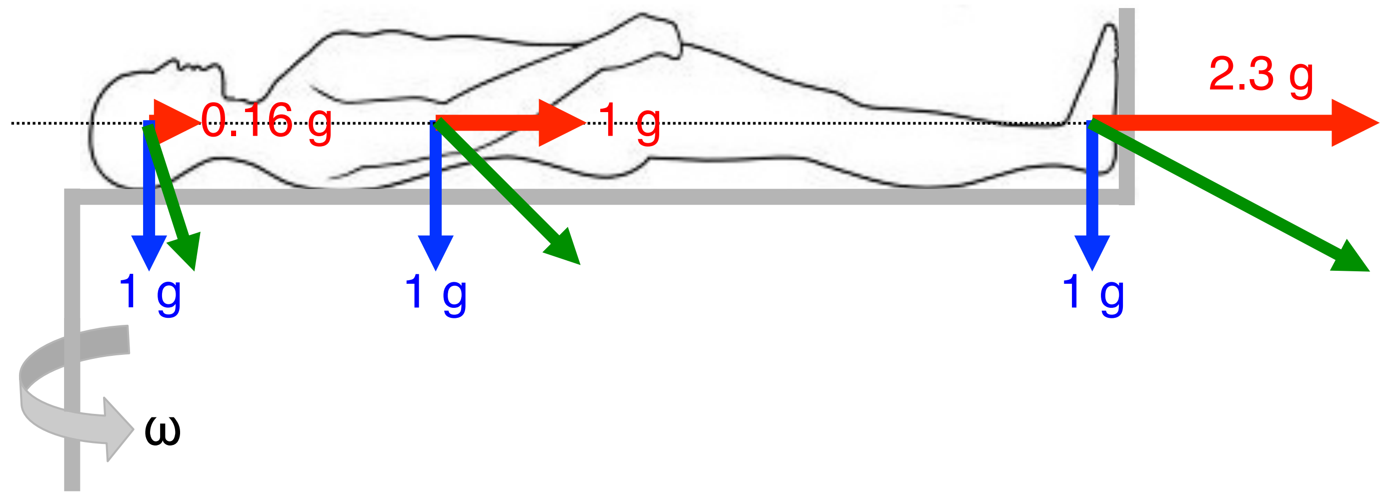
Short-Radius Centrifugation on Earth



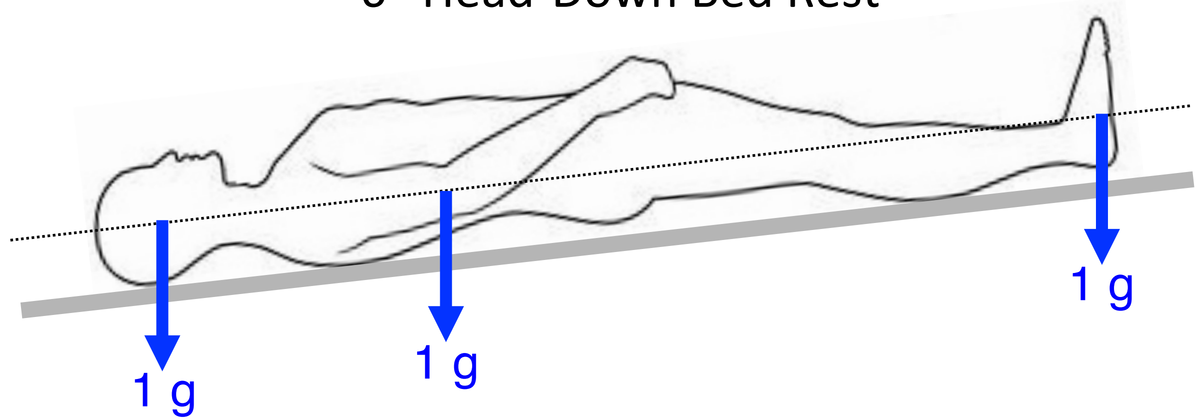
SR Centrifugation in Space



Short-Radius Centrifugation on Earth



-6º Head-Down Bed Rest



Adaptation to Rotating Environments

- **Rotation studies (Graybiel 1960-1965)**
  - Slow rotating room (SRR) – 2.3-m radius
  - SRR accelerated from rest to 1, 1.71, 2, 2.21, 3.82, 5.44, 7.5 & 10 rpm (single-step)
  - Below 3.82 rpm adaptation took place in minutes.
  - At 3.82 rpm adaptation took place in hours.
  - At 5.44 and 7.5 rpm all subjects were <u>partially</u> incapacitated by motion sickness, disruption of movement control, and fatigue. Consequently, they greatly reduced their movement and spent much time sleeping.
  - At 10 rpm all subjects were <u>severely</u> incapacitated by motion sickness and fatigue, and never were able to make normal head and body movements.
- On the basis of these studies it is often claimed that rotation rate for AG should be **4 rpm or below**.

Adaptation to Rotating Environments (cont'd)

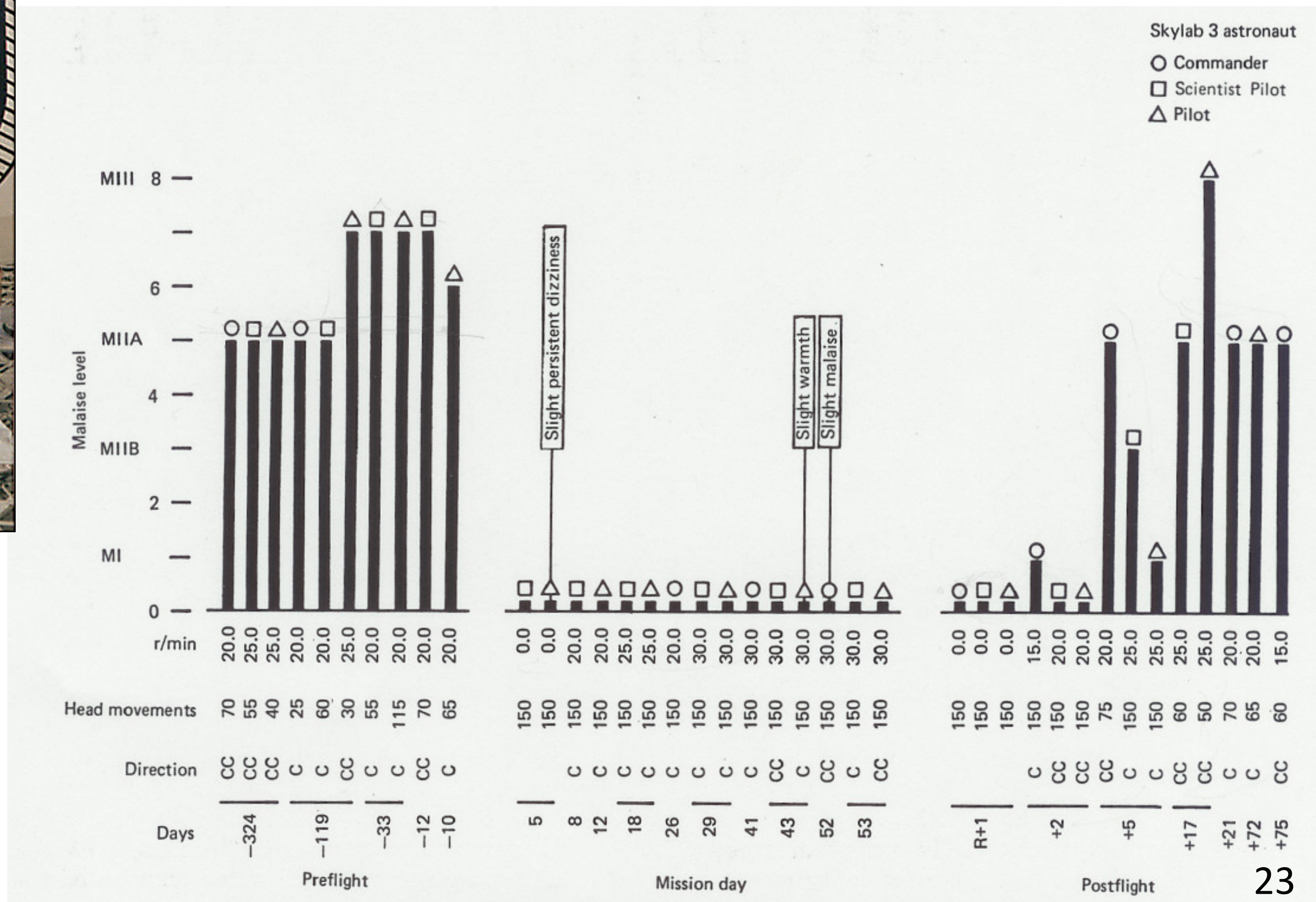
- **SRR studies in the 1960s:**
  - Were preliminary and involved a total of only 30 subjects
  - Did not attempt to identify optimum exposure and training strategies to adapt people to rotating environments
- **Since then, it was found that:**
  - No motion sickness is experienced when rotation rate is achieved incrementally, e.g. in 1-rpm steps or more (Graybiel & Knepton 1978; Young et al. 2001)
  - Motion sickness decreases after repeated exposure to cross-coupled accelerations (Clément et al. 2001)
  - Adaptation of arm, leg, and head movement control to rotation rates of 10 rpm and higher (Lackner & Dizio 2000)

Adaptation to Rotating Environments (cont'd)

- **Concern #1: Whether the responses to Coriolis and cross-coupled accelerations and the ability to achieve adaptation will be the same in 0 g as in 1 g**
  - Skylab M-131 found that head movements made during rotation failed to induced motion sickness on orbit
  - In parabolic flight, side effects are more severe at 2 g and less intense at 0 g than in 1 g.
  - In parabolic flight, deviation of movement path similar at 0 g, 1 g, and 2 g.

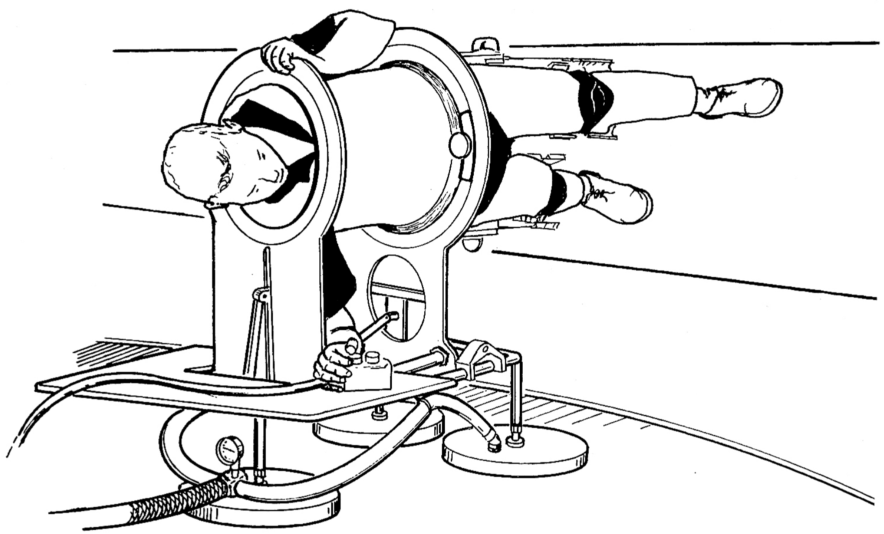
Skylab Experiment M131

Graybiel A, Miller EF, Homick JL (1977) Experiment M131. Human vestibular function. In: Johnston RS, Dietlein LF (eds) Biomedical Results from Skylab. NASA: Washington DC, NASA SP-377, pp 74-103

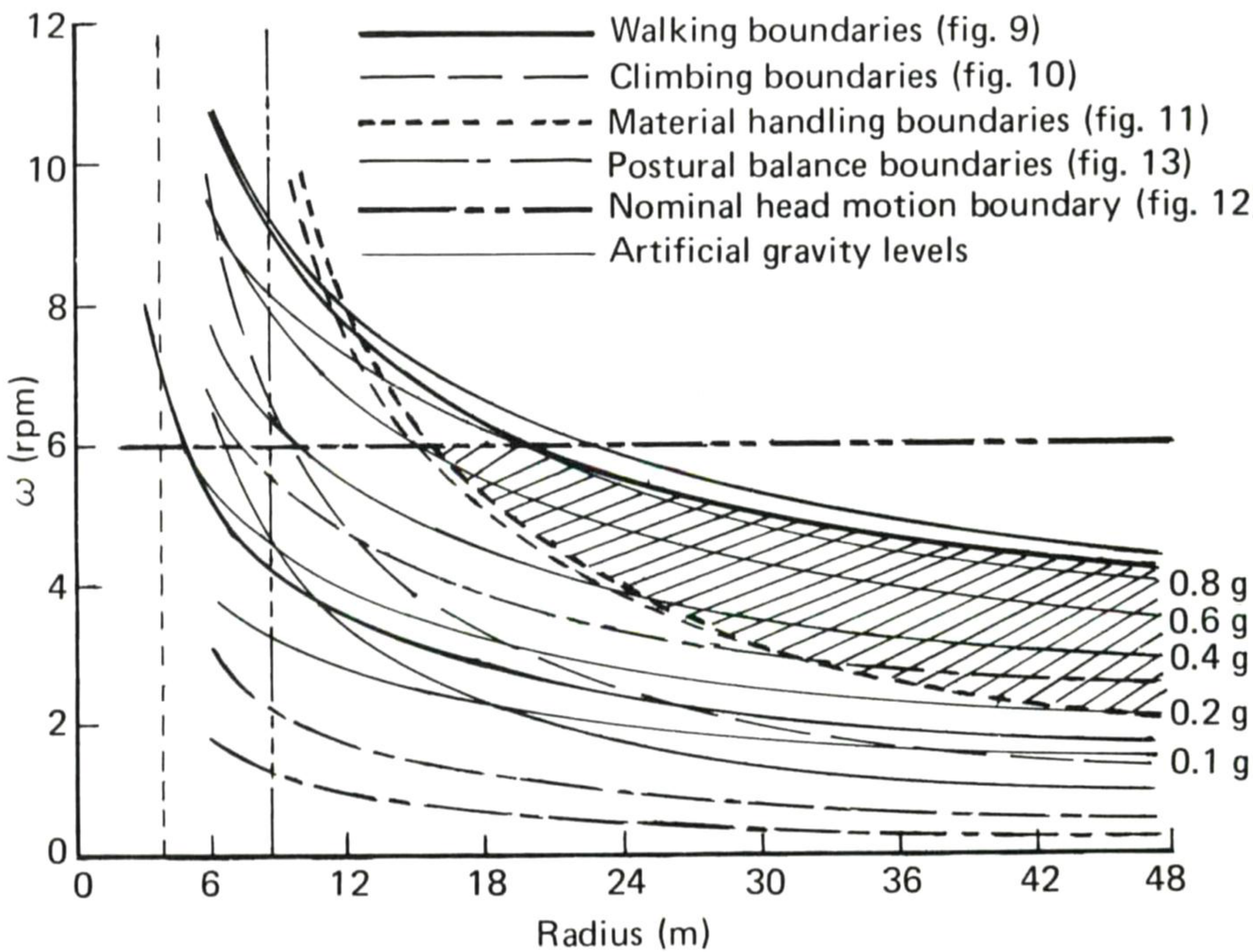


Adaptation to Rotating Environments (cont'd)

- **Concern #2: Whether adaptation to SRR on Earth, where AG is almost parallel to rotation axis, will transfer to rotation of a space vehicle, where AG will be orthogonal to the spin axis :**
  – Body movements made from a starting posture parallel vs. orthogonal to the spin axis generate different Coriolis and cross-coupled accelerations
  – Motion sickness adaptation transferred between body orienta[…] al. 1968)



Model – some validation required



Stone & Letko (1965)

AG with Humans – What Do We Know ?

- Artificial gravity was first tested on humans in space in 1966 during the **Gemini-11** flight
  - The spacecraft was tethered to an Agena target vehicle by a long Dacron line, causing the two vehicles to spin slowly around each other ($r = 200$ m, $\omega < 1$ rpm, AG < 0.001 g)
  - According to the Gemini commander, a TV camera fell "down" in the direction of the centrifugal force, but the crew did not perceive any changes

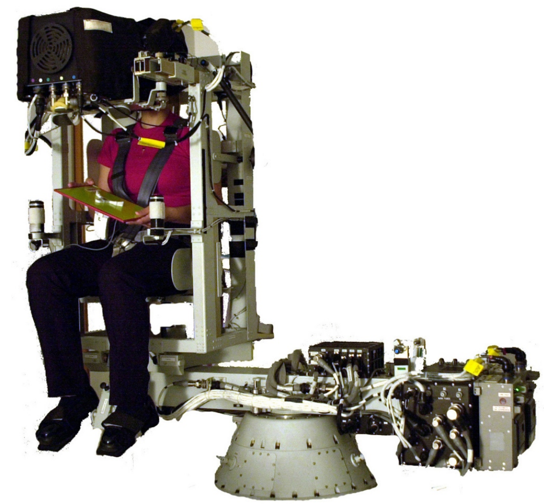
What Do We Know? (cont'd)

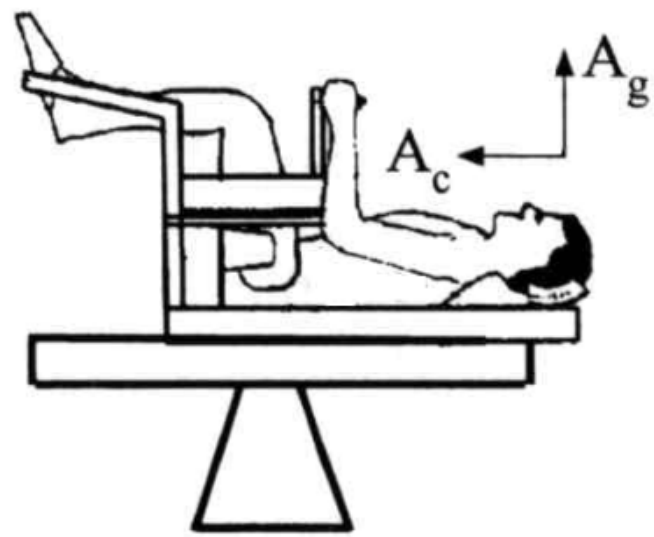
- **Vestibular investigations** on board STS-42 (IML-1, 1992)
  - NASA Spacelab Rotator – PI: M Reschke (NASA)
  - Axis of rotation aligned with subject's center of mass. Head and feet were off-center by about 0.6 m
  - Rotation at 20 rpm for one minute generated a centripetal acceleration of 0.22 g
  - +Gz at the feet
  - –Gz at the head

NASA Spacelab Rotator

What Do We Know? (cont'd)

- **Vestibular investigations** on board STS-90 (Neurolab, 1998)
  - ESA Off-Axis Rotator – PI: G Clément (CNRS)
  - Gy centrifugation – Subject off-center by 0.5 m
  - Gz centrifugation – Axis of rotation aligned with subject's center of mass (r = 0.65 m)
  - Rotation at 42 rpm for 7 min generated +1.0 Gy (body)
  - Rotation at 37 rpm for 7 min generated +1.0 Gz at feet and –1.0 Gz at head

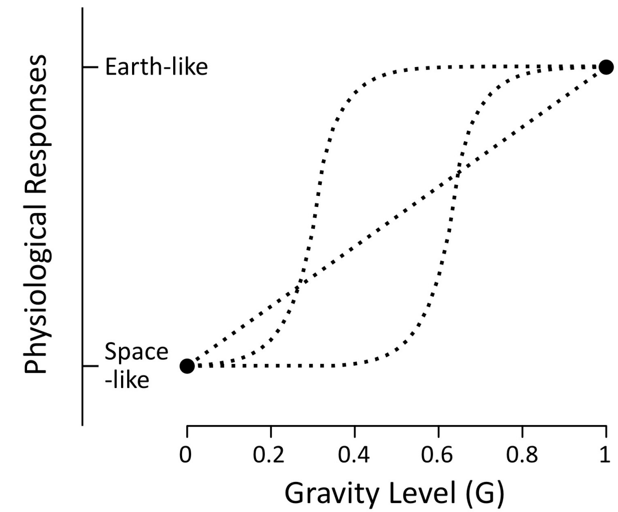




ESA Off-Axis Rotator

AG Research Approach

- **"G dose-physiological response" curve**
  - Acute studies – rats (suspension) & humans (parabolic flight, unloading)
  - Chronic studies – mice (JAXA ISS centrifuge)
- **Duration of AG exposure**
  - Continuous – rats (ground-based centrifuge)
  - Continuous – mice (JAXA ISS centrifuge)
  - Intermittent – humans (bed rest)
- **Health consequences of AG**
  - Cross-coupled and Coriolis accelerations (SRR)
  - Gravity gradient (large-radius centrifuge)
  - Combination with exercise
- **Validation of AG prescription in orbit**
  - Models
  - Comparison between ground and on-orbit AG prescription – mice
  - Flight AG demonstration with humans – HTV-X
  - Flight AG validation with humans – DSH



HRP AG Research Plan (Jan 2017)

			2017	2018	2019	2020	2021	2022	2023	2024	> 2024
Objective	Platform	Task	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
AG Level	Earth	G dose-response in rodents during SRC									
	Analogs	G dose-response using computational models									
		G dose-response in rats during suspension									
		G dose-response in humans during suspension									
		G dose-response in humans during water immersion									
		G dose-response in humans during head-up tilt (HUT)									
		G dose-response in humans during parabolic flight									
	ISS	G dose-response in mice using MHU on board the ISS									
		G dose-response in rats using RCF on board the ISS									
Mars Gravity	Earth	Martian gravity in humans during body unloading									
		Martian gravity in humans during HUT bed rest									
		Martian gravity in returning ISS crew during HUT									
	ISS	Martian gravity in rats using RCF on board the ISS									
AG Duration	Earth	Intermittent rotation in rats after SRC on Earth									
		Intermittent rotation in humans during HDT bed rest									
		Continuous rotation in humans in live-aboard habitat									
	ISS	Intermittent rotation in rats on board the ISS									
Health	Earth	Health consequences of gravity gradient in LRC									
		Effects of centrifugation on ICP in healthy subjects									
		Effects of centrifugation on ICP in analog VIIP patients									
		Health consequences of Coriolis and CCA in SRR									
Validation	Earth	Requirements for AG studies on board the DSH									
		Ground-based studies using the DSH centrifuge									
	ISS	Effectiveness of the AG prescription in rats on the ISS									
	HTV-X	Human short-radius centrifuge on space operations									
	DSH	Short-term effects of AG prescription in humans in orbit									

NRA Jun 2015

NRA Oct 2015

NRA Apr 2017

Planned

HRP AG Research Plan (Jan 2017)

Objective	Platform	Task	2017	2018	2019	2020	2021	2022	2023	2024	> 2024
			1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
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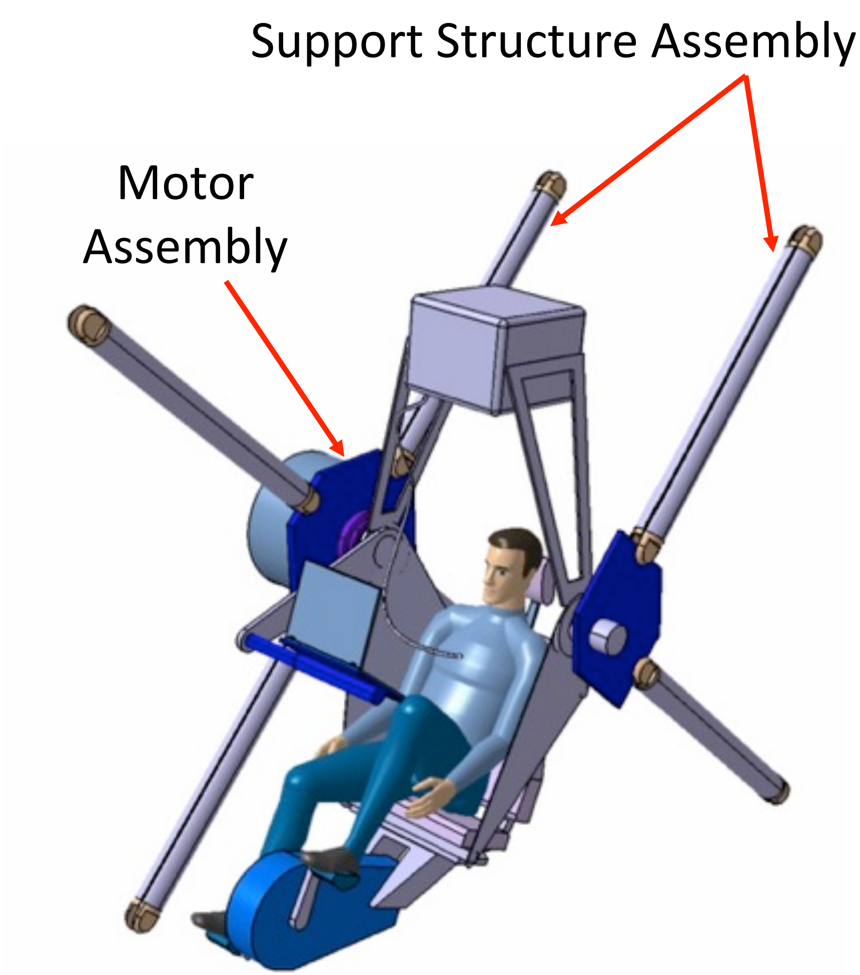
NRA Jun 2015

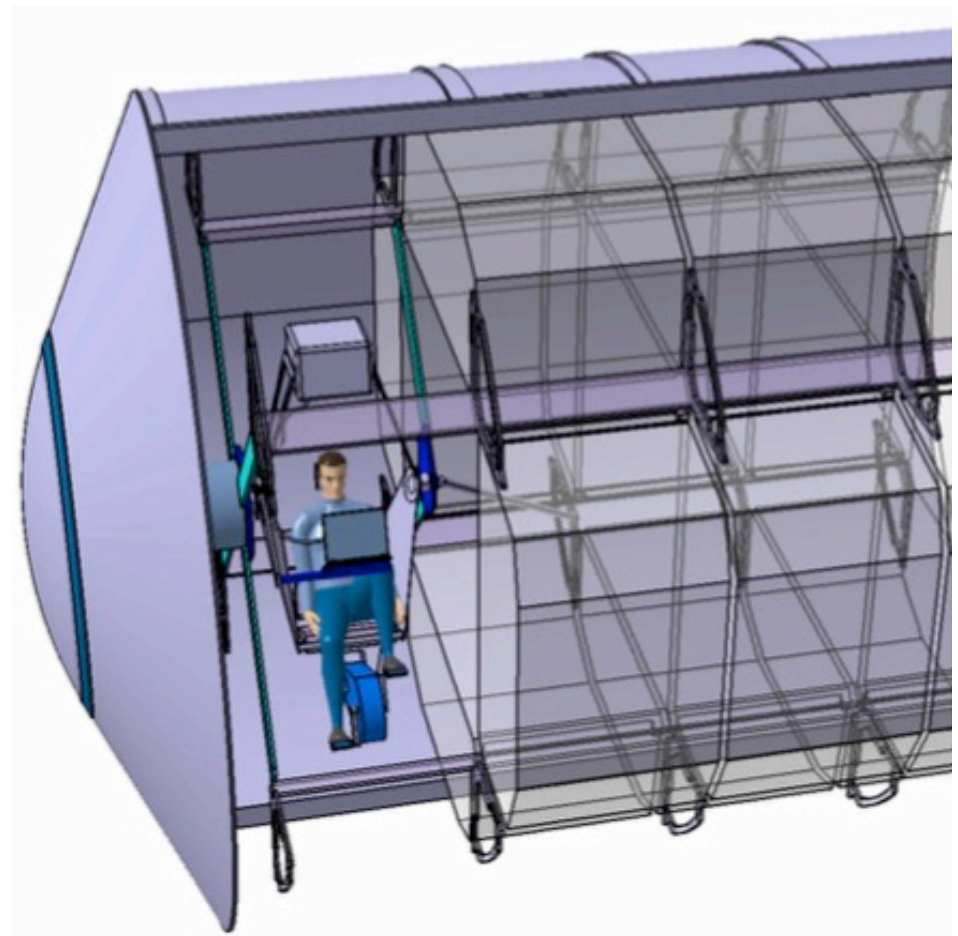
NRA Apr 2017

NRA Oct 2015

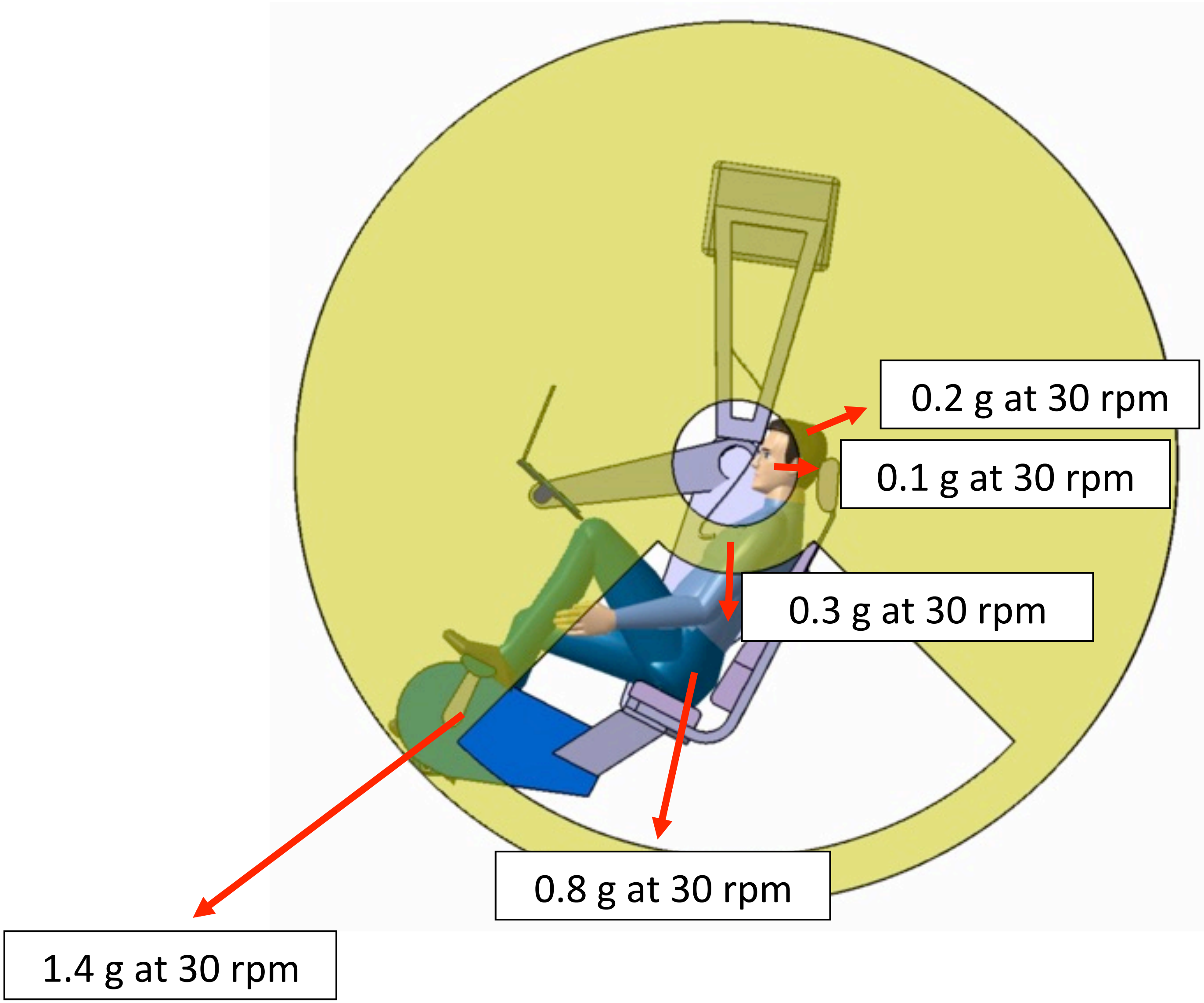
Planned

ISS AGREE Project (2011)

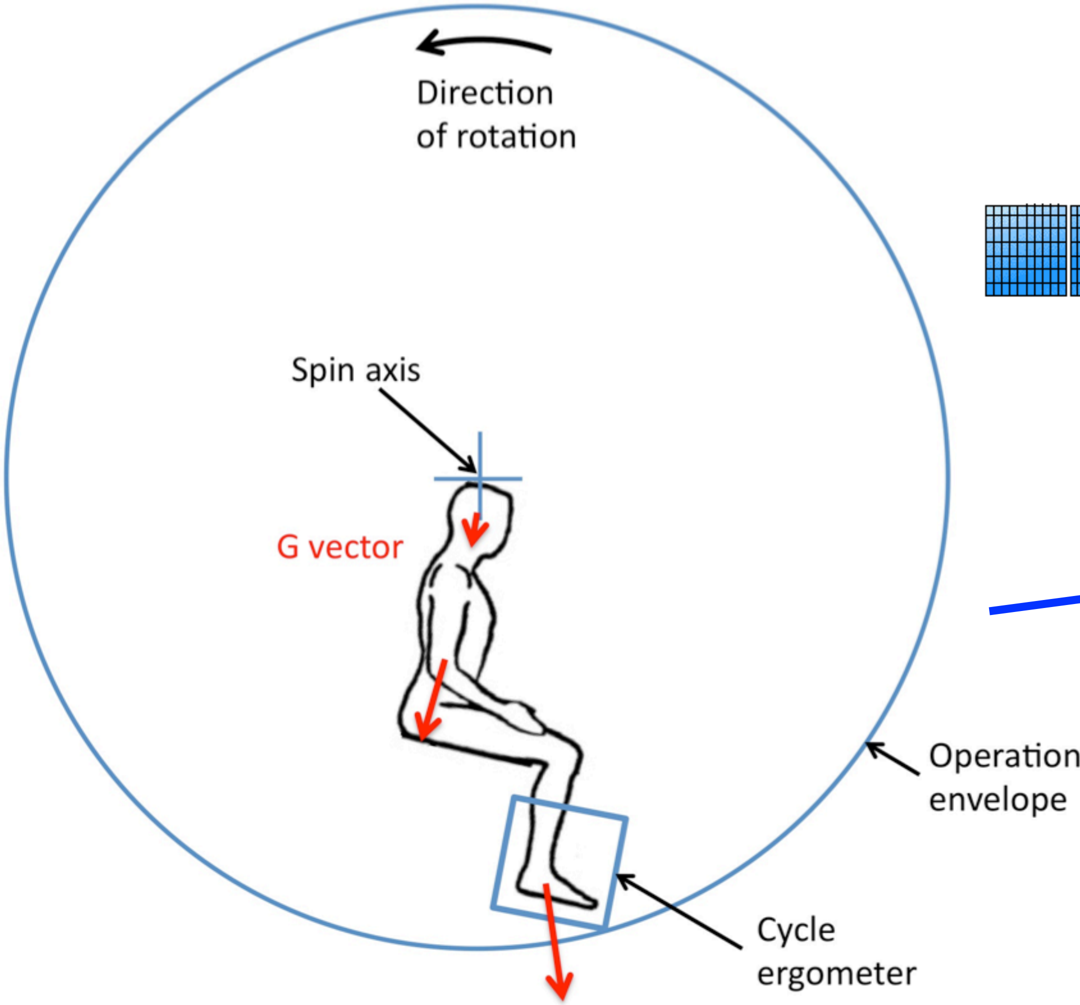


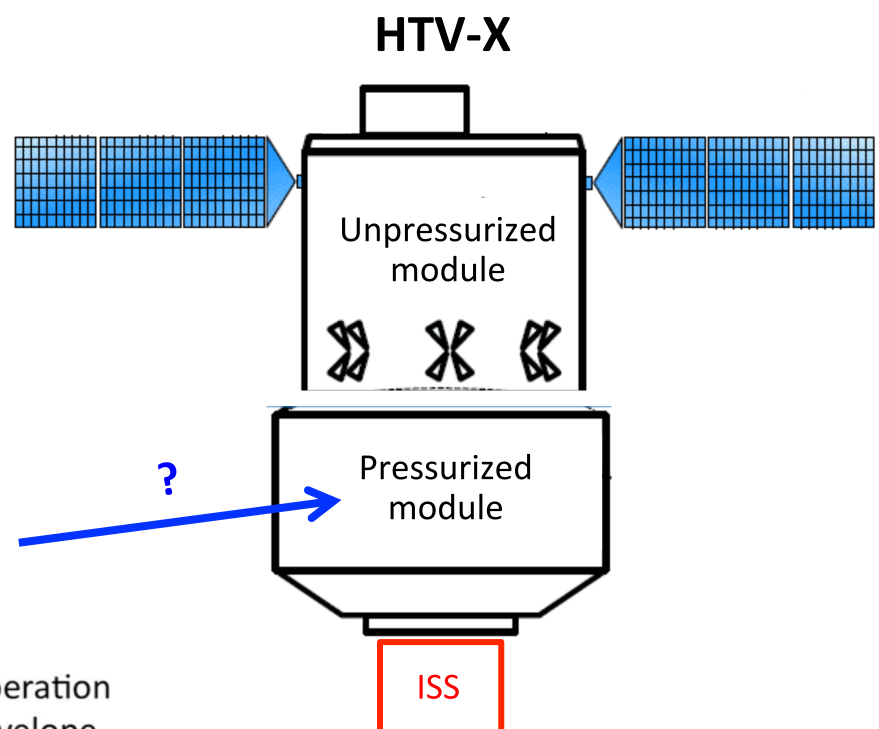


ISS AGREE Gravity Gradient



HTV-X Human Centrifuge Project





HTV-X Human Centrifuge Objectives

- **Subjective Assessment**
  - Crew comfort – nominal and max RPM
  - Safety issues
  - Crew time
  - Crew overall acceptance
- **Engineering Assessment**
  - Loads at interfaces with module/node
  - Vibrations, g jitters, noise
  - Heat load
  - Air flow

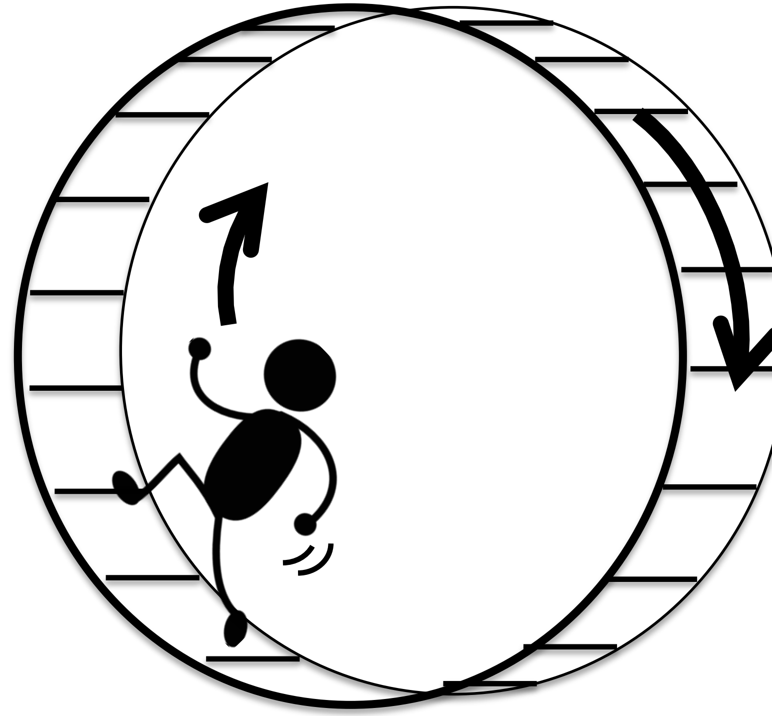
CEVIS

- **Physiological Assessment – AG as a countermeasure**
  - Compare CEVIS and centrifuge
  - E.g., CEVIS during first half of Expedition, centrifuge during second half of Expedition (vice-versa with 2nd subject)

Spinning Track

Skylab 2 (1973)

- Radius: 3.3 m
- Rotation rate: 6.5 rpm
  - 0.15 g at feet



- Radius: 5 m
- Track rotation rate: 6 rpm
- Subject rotation rate: 9 rpm
  - 1 g at center of mass
  - 1.3 g at feet