Artificial Gravity for Exploration Class Missions?

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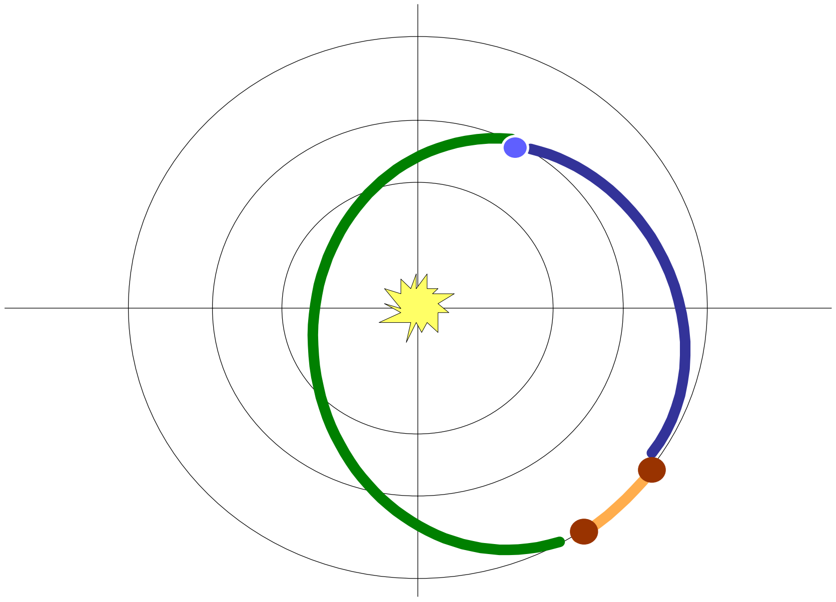
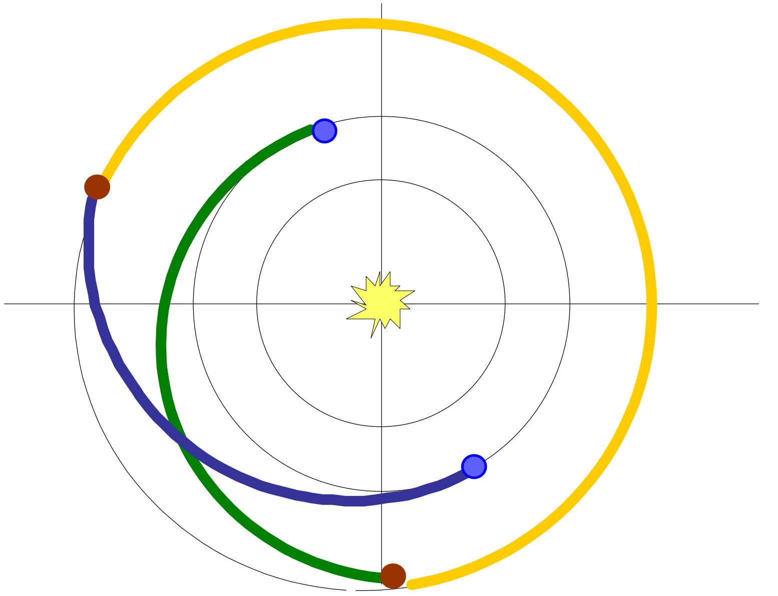
Mars Trajectory Options



One-Year Mission



Three-Year Mission

Outbound
Surface Stay
Inbound

Ref. Johnson Space Center

Factors Affecting Human Health and Performance During Space Flight

decreased gravity

bone, muscle, cardiovascular, neurosensory, nutrition, behavior/performance, immunology, clinical medicine

isolation/confinement

behavior/performance, nutrition, immunology, toxicology, microbiology

altered light-dark cycles

behavior/performance

increased radiation

immunology, carcinogenesis

Current Countermeasure Concepts

bone

resistive exercise, bis-phosphonates, whole-body vibration, ..., artificial gravity

muscle

resistive & aerobic exercise, growth hormone, ..., artificial gravity

cardiovascular

aerobic exercise, midodrine, LBNP, ..., artificial gravity

neurosensory

artificial gravity, ???

CM Concerns for Mars Mission

research/development/evaluation/validation

time, cost, flight resource requirements (n!)

operational effectiveness

equipment reliability

drug interactions, side effects

complexity: crew time, crew compliance

Is AG a better solution?

Selected Early History of AG

Tsiolkovsky, K.E. (1903) *Exploration of Space With Rocket Devices*

Tsiolkovsky, K.E. (1920) *Beyond the Planet Earth*

Ganswindt, H. (1920)

Oberth, H. (1923) *The Rocket into Planetary Space*

Noordung, H. (1928) *The Problem of Exploring Space*

Bernal, J. D. (1929) *The World, the Flesh, and the Devil*

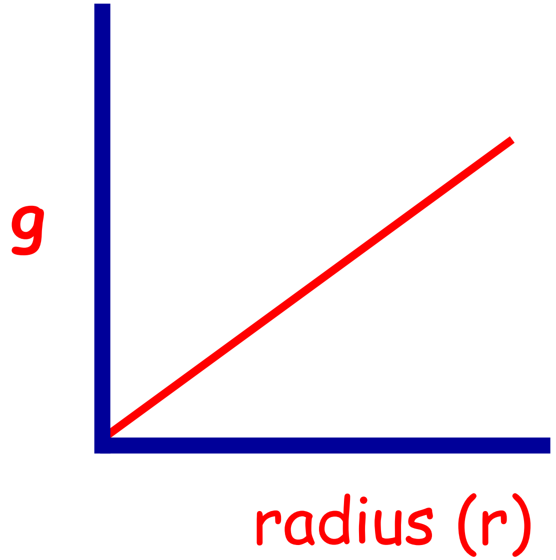
Von Braun, W.(1952) *Crossing the Last Frontier*

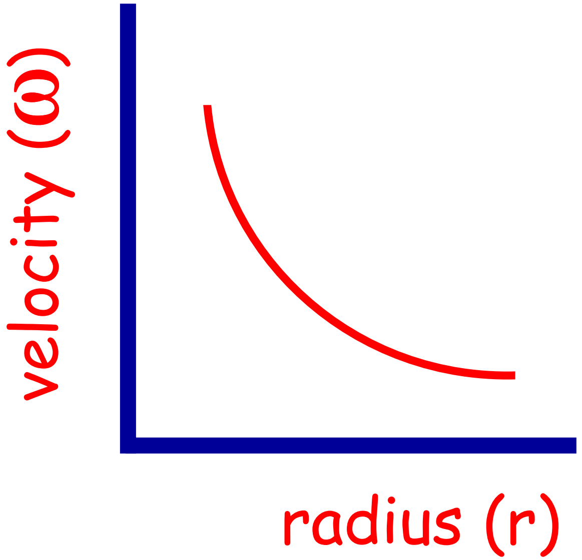
Clark, A.C. and Kubrick, S. (1968) *2001: A Space Odyssey*

Physics of Rotating Environments

Artificial Gravity Level (Centripetal Acceleration)

$$g = r\omega^2$$

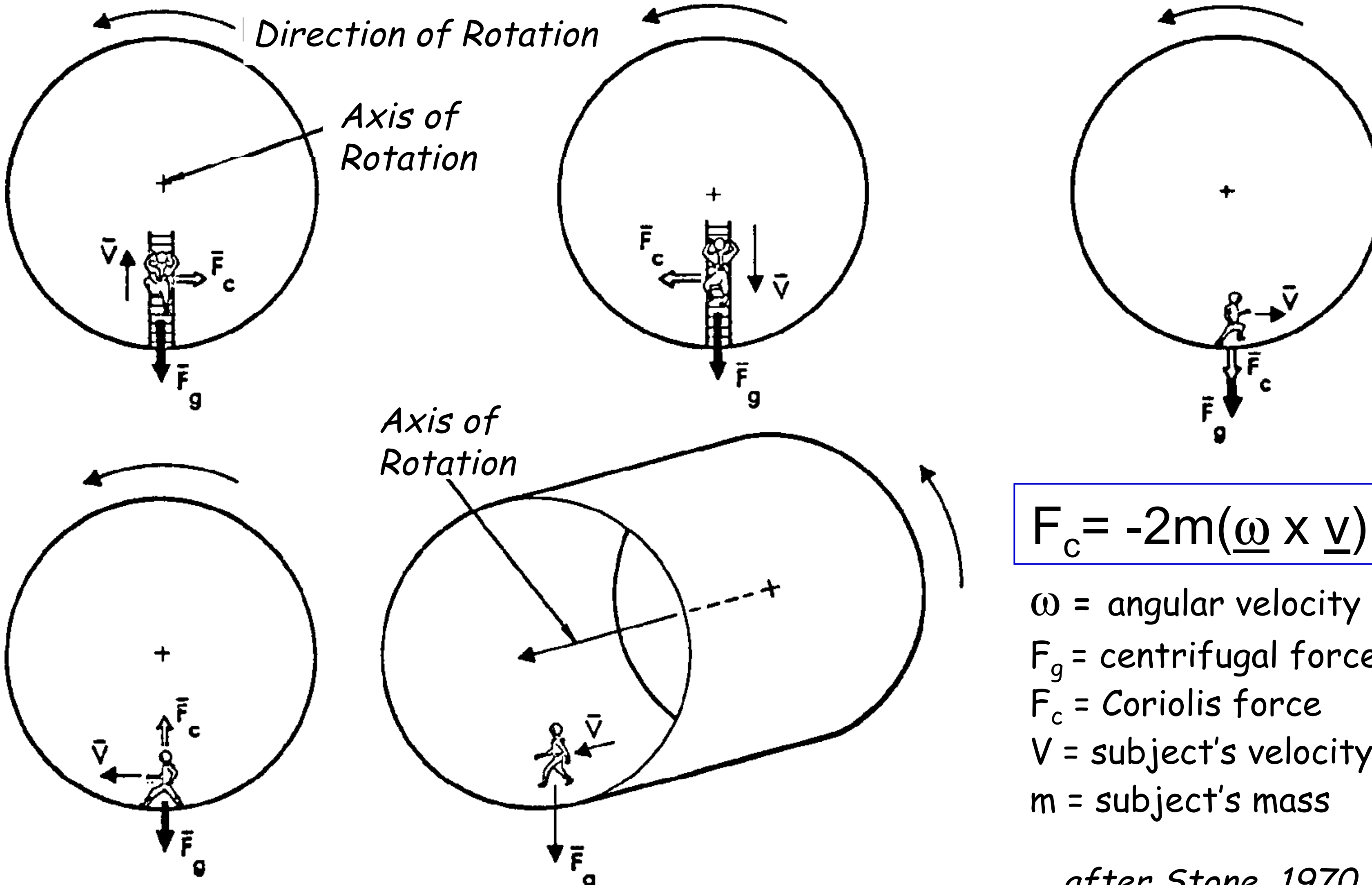




Artist's Concept of AG Ops

from Kubrick, 1968

Coriolis Force Effects



$$F_c = -2m(\underline{\omega} \times \underline{v})$$

ω = angular velocity

F_g = centrifugal force

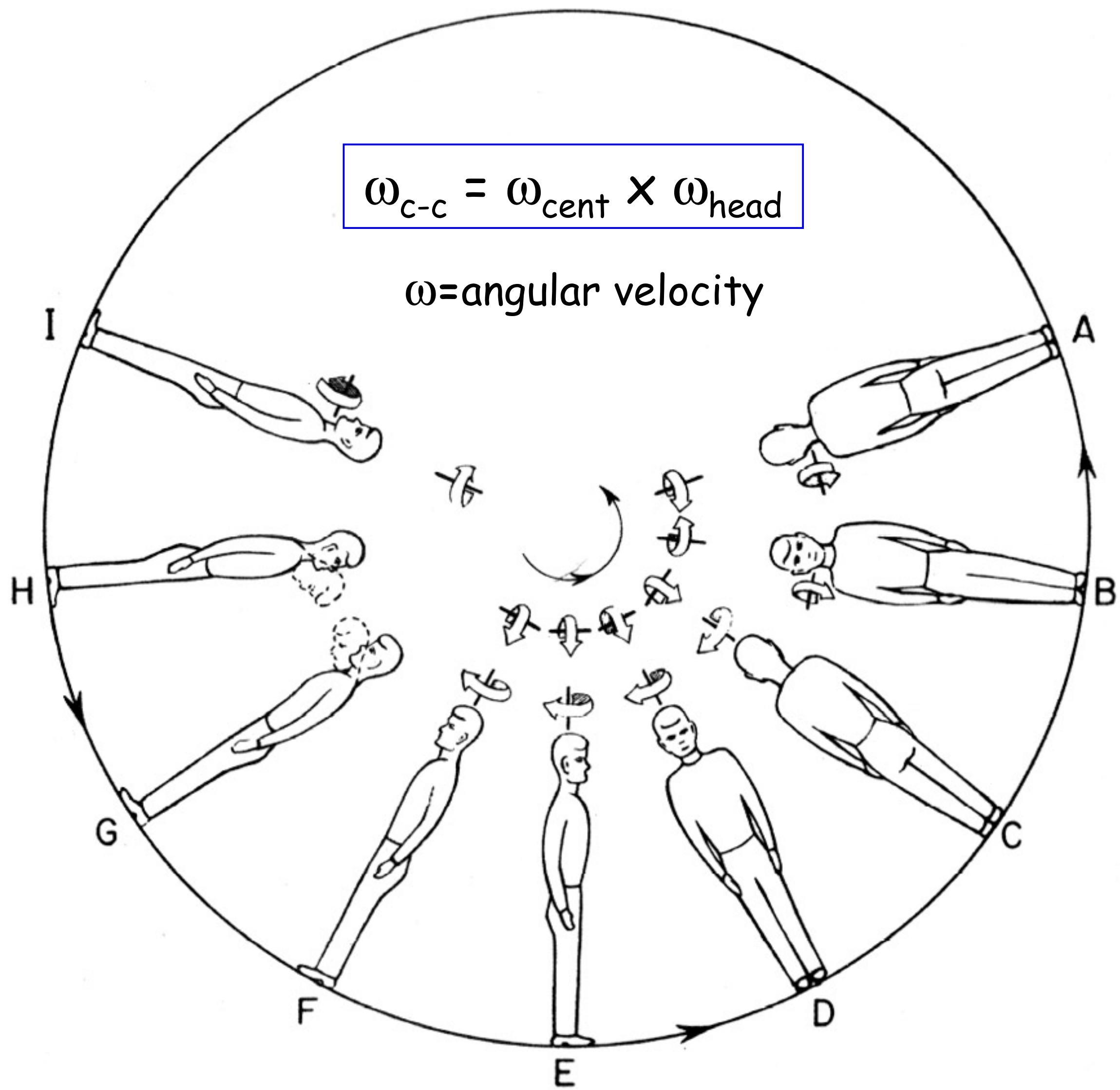
F_c = Coriolis force

V = subject's velocity

m = subject's mass

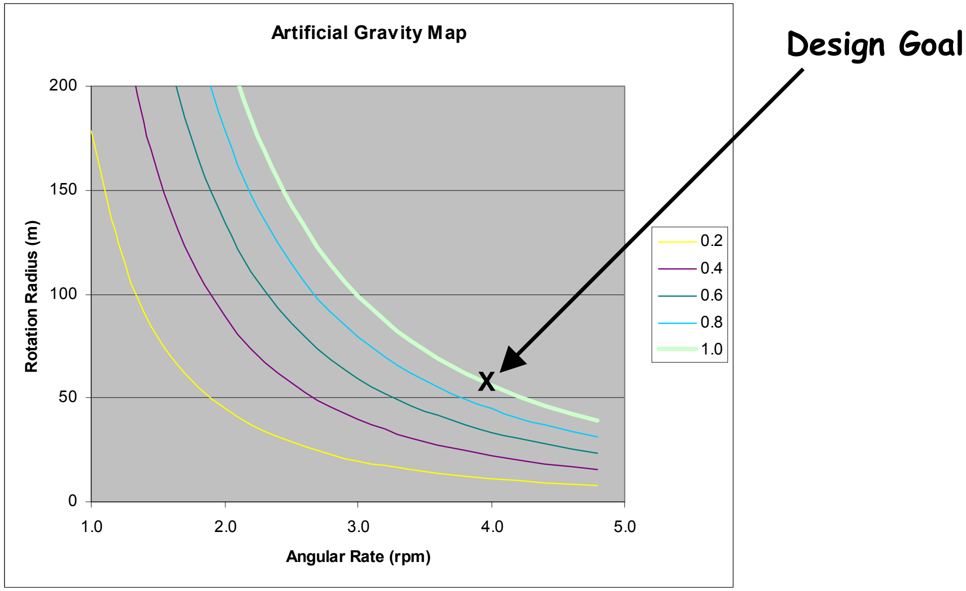
after Stone, 1970

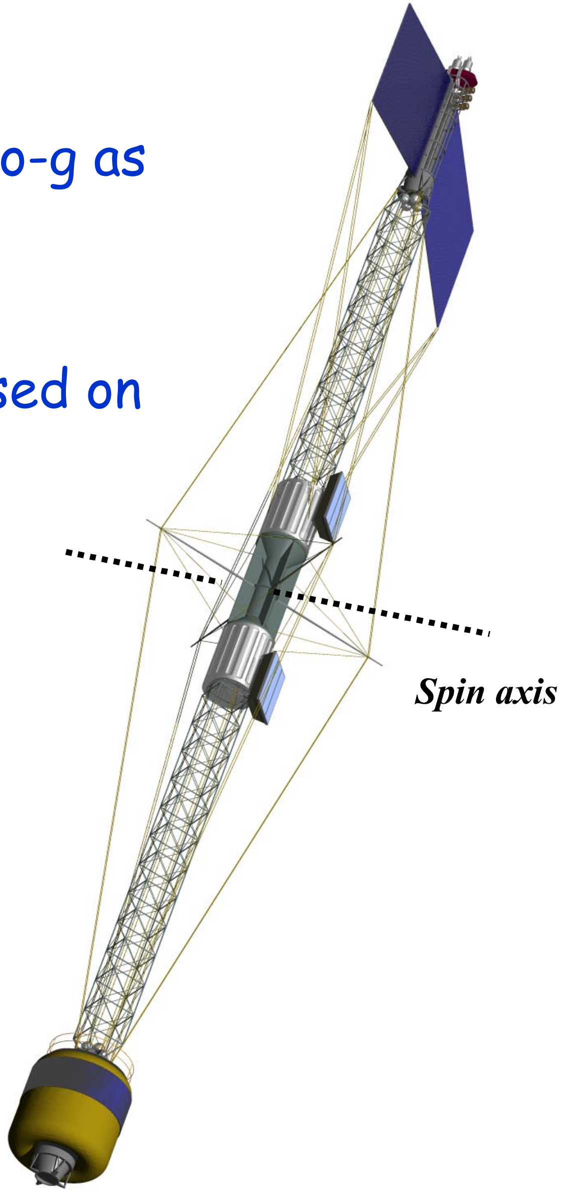
Cross-Coupling Effects



Mars Mission Concept 1

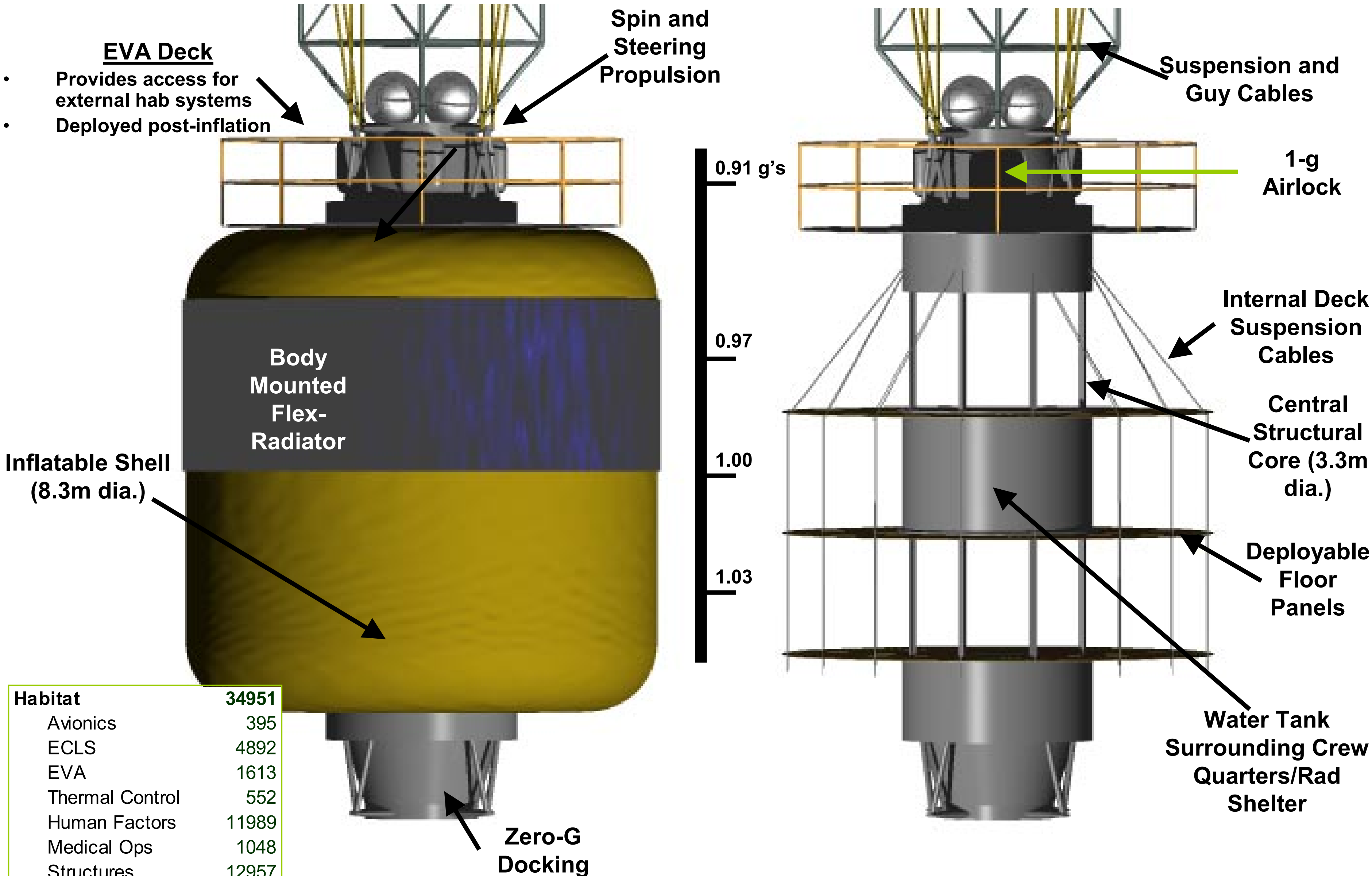
- Nominal design = 1.0 g
  - Essentially no data on efficacy of hypo-g as countermeasure
- Rotation levels ≤ 4 rpm
  - Acceptable crew adaptation times based on rotating room studies
- Implies radius of ≥ 56 meters





Courtesy of K. Joosten

Crew Module Concept



Habitat	34951
Avionics	395
ECLS	4892
EVA	1613
Thermal Control	552
Human Factors	11989
Medical Ops	1048
Structures	12957
Power	1505

Decision for Spinning Vehicle

Benefits:

-physiological adaptation in-transit (bone, muscle, cardio, neuro, …)

-human factors in-transit (spatial orientation, WCS, galley, …)

-medical equipment/operations (countermeasures, surgery, CPR, …)

-environmental (particulates, liquids, …)

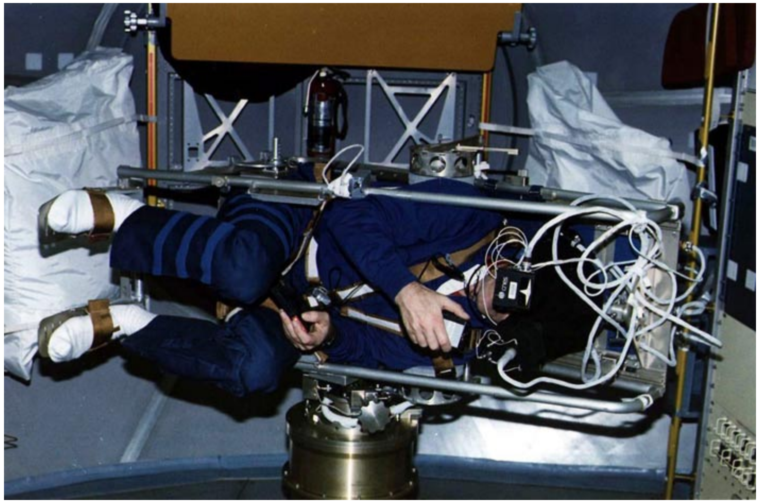
Risks/Uncertainties:

-engineering (requirements, design: truss, fluid loops, propulsion…)

-human factors during spin-up/down

-physiological adaptation during spin-up/down (neuro, cardio, …)

Short-Radius, Intermittent AG



Mode Tradeoffs

Long-radius, continuous

- passive
- single adaptation
- expensive? (up mass)

Medium radius, intermittent

- passive part of day
- adaptation? vestibular, cardiovascular

Short-radius, intermittent

- reliability?
- adaptation? vestibular, cardiovascular
- duty cycle?
- effectiveness? vestibular, cardiovascular

AG Research Questions

To validate AG as an effective countermeasure for the bone, muscle, cardiovascular, neurovestibular, and other target physiological systems:

How much AG is needed to maintain physiological function/ performance?	• What are the physiological thresholds for effective gravitational force? • What minimum and/or optimum g-force should be used during transit? • Would AG be required on the Lunar or Martian surface?

What are the acceptable and/or optimal ranges for radius and angular velocity of a rotating space vehicle or centrifuge?	• What are the untoward physiological consequences of rotational AG? • What are the physiological limits for angular velocity, g-gradient, etc.? • What duty cycle is optimal for intermittent applications?

What additional countermeasures would be required to supplement AG?

after Paloski & Young, 1999

Artificial Gravity Project

Investigator Initiated Studies (NASA and NSBRI)

- system specific
- ground and flight components
- observational/mechanistic (human/animal)

Team Studies

- multi-system, multi-center
- ground and flight components
- observational/mechanistic/parametric (human/animal)

-International Multi-discipline AG Bed Rest (IMAG) Project

- intermittent exposure/deconditioned subjects
- centrifuge + exercise and other cm's

-Live-Aboard Studies Project

- continuous exposure
- long-radius centrifuge and/or slow rotating rooms (human/animal)

-Flight Research Project

- intermittent exposure/space flight subjects (human/animal)
- CAM, human SRC aboard ISS, rotating lunar CEV

AG Project Team Studies Content

- **IMAG Short Radius Centrifuge (Phases 1, 2, 3)**
  - Prescription to protect bone, muscle, cardio(?), neuro(?),
  - Capacity for adaptation: neuro, cardio (fluid shifts)
  - Lead to flight testing (prescription validation, vestibular responses, ?)
- **Long Radius Centrifuge/Slow Rotating Room**
  - Sensory-motor adaptation
  - Human factors
  - Effects of g-gradient (deconditioned subjects)
- **Animal Studies (Rodent, Rhesus; Ground, CAM)**
  - Larger n, Quicker answers, Lower costs than humans
  - Preliminary results guide human studies

IMAG Project Phases

Pilot Study
12-18 months
US only (UTMB)

Science Phase
~5 years
UTMB, IMBP, DLR

Flight Demo
~5 years
ISS

Pilot Study Design

Subjects: 32 human subjects

- Screened to match astronaut population
- 50% male, 50% female
- 16 control (no countermeasure)
- 16 treatment (AG countermeasure)

Deconditioning Stimulus: 21 days of 6° head-down bed rest (at UTMB GCRC)

Countermeasure: daily 1 hr doses of AG

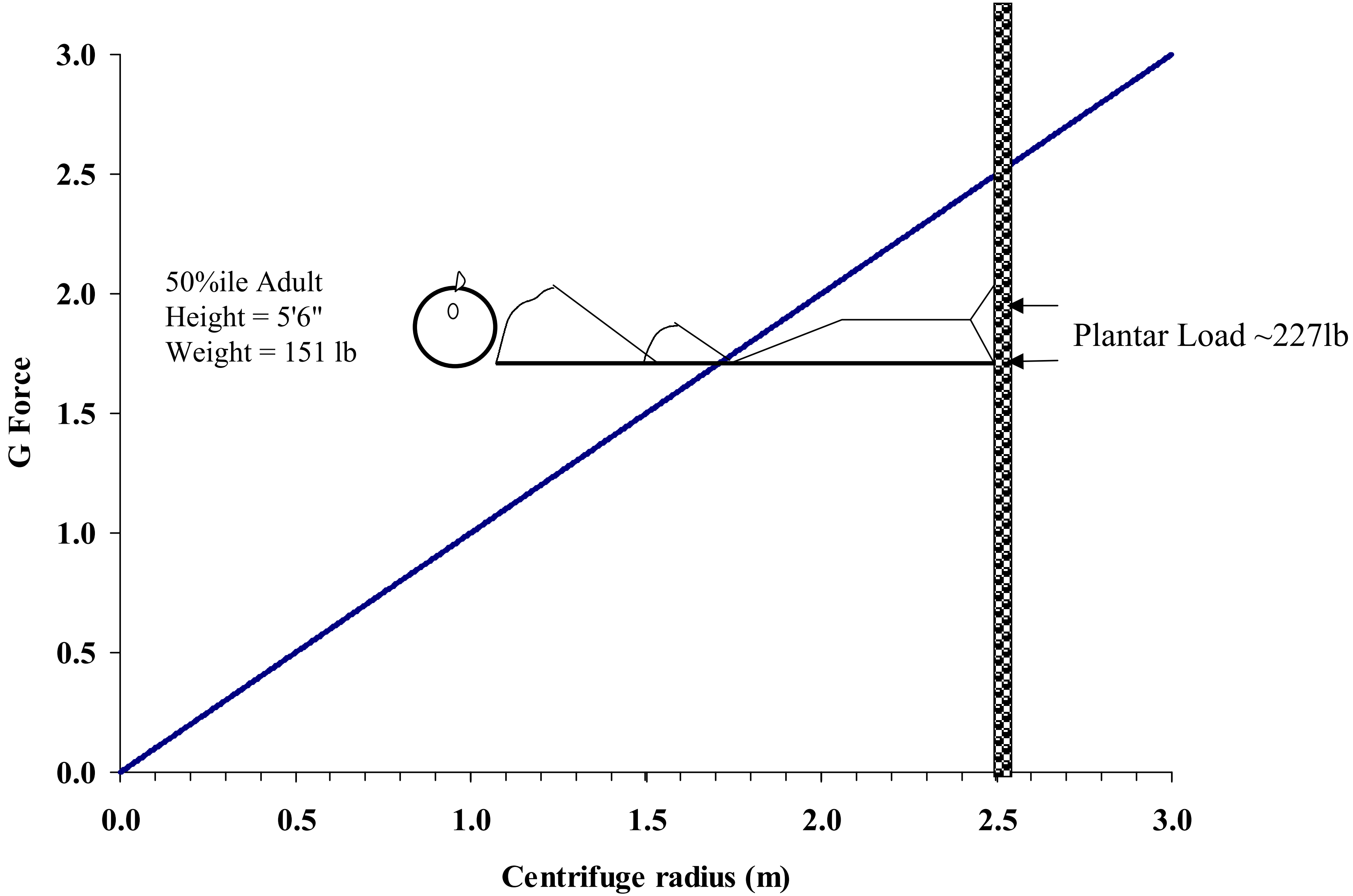
- Nominally 2.5 g at feet (base-of-support)

Dependent Measures:

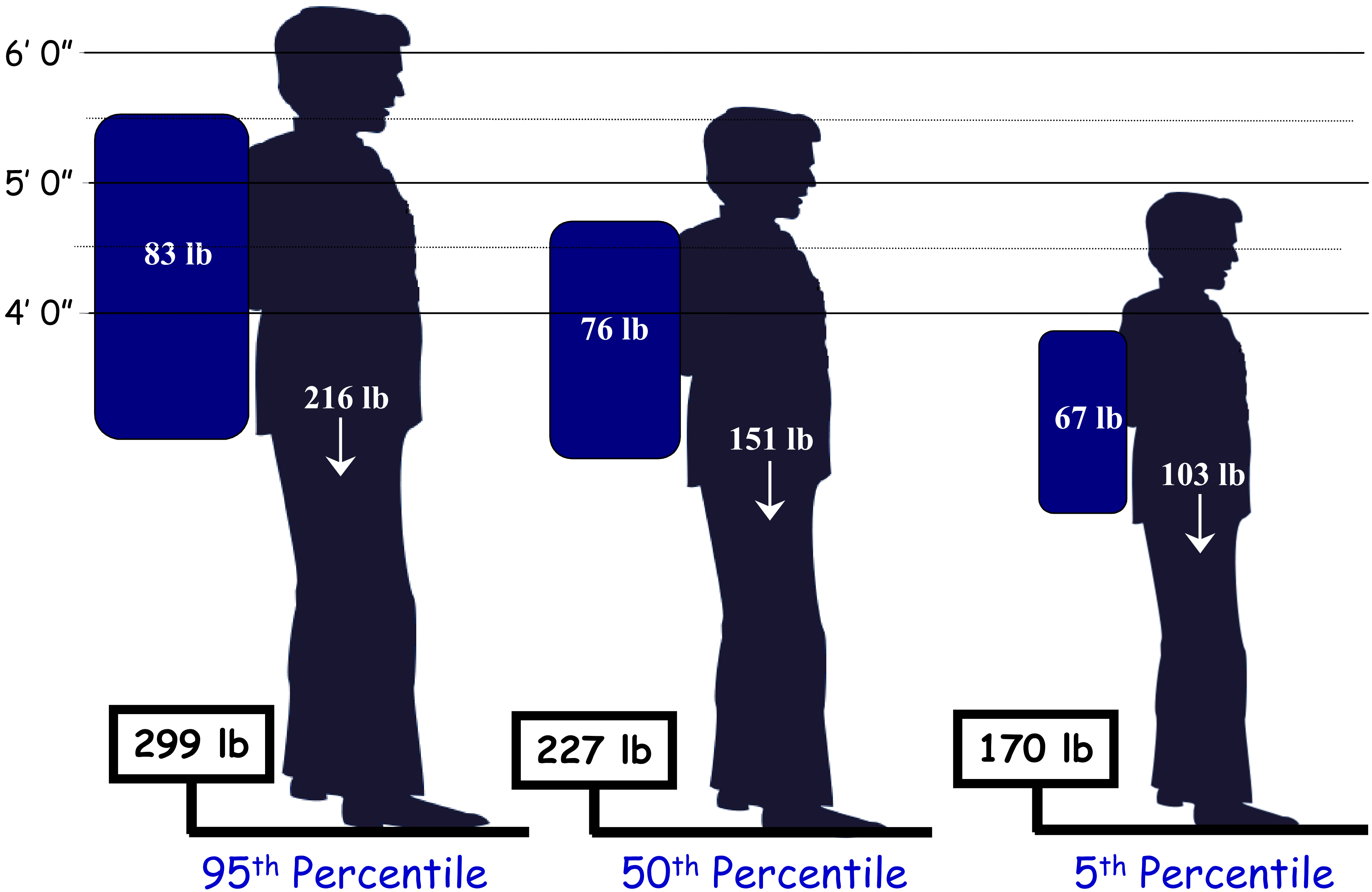
- Multiple per system (operational & mechanistic)
- Downward compatible with space flight standards

IMAG Pilot Study Centrifuge

G-Loading on Centrifuge

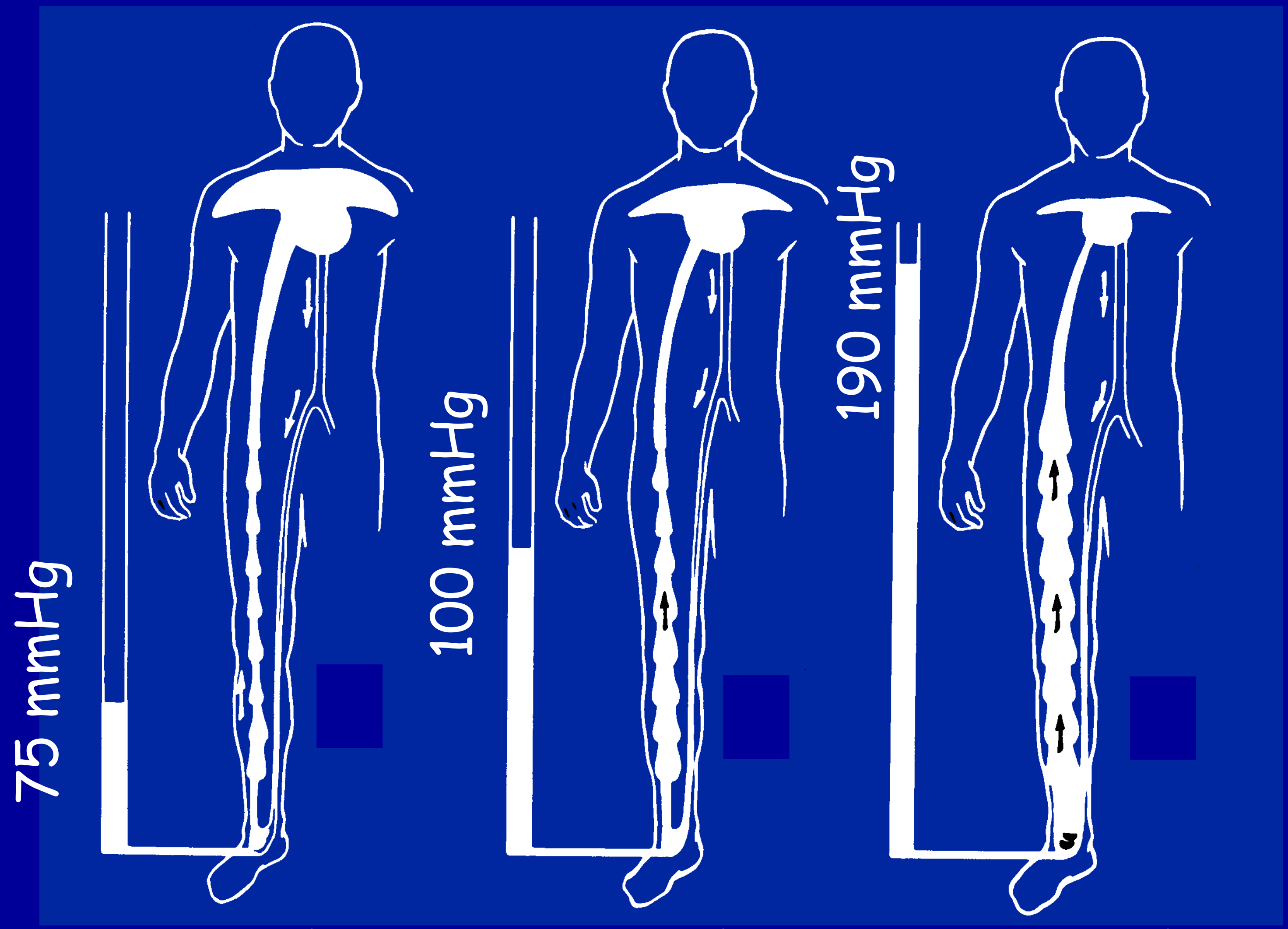


Weight Increase During Spins



pilot study spins = 2.5 g at feet on 2.5 m radius centrifuge

Fluid Shifts During Spins

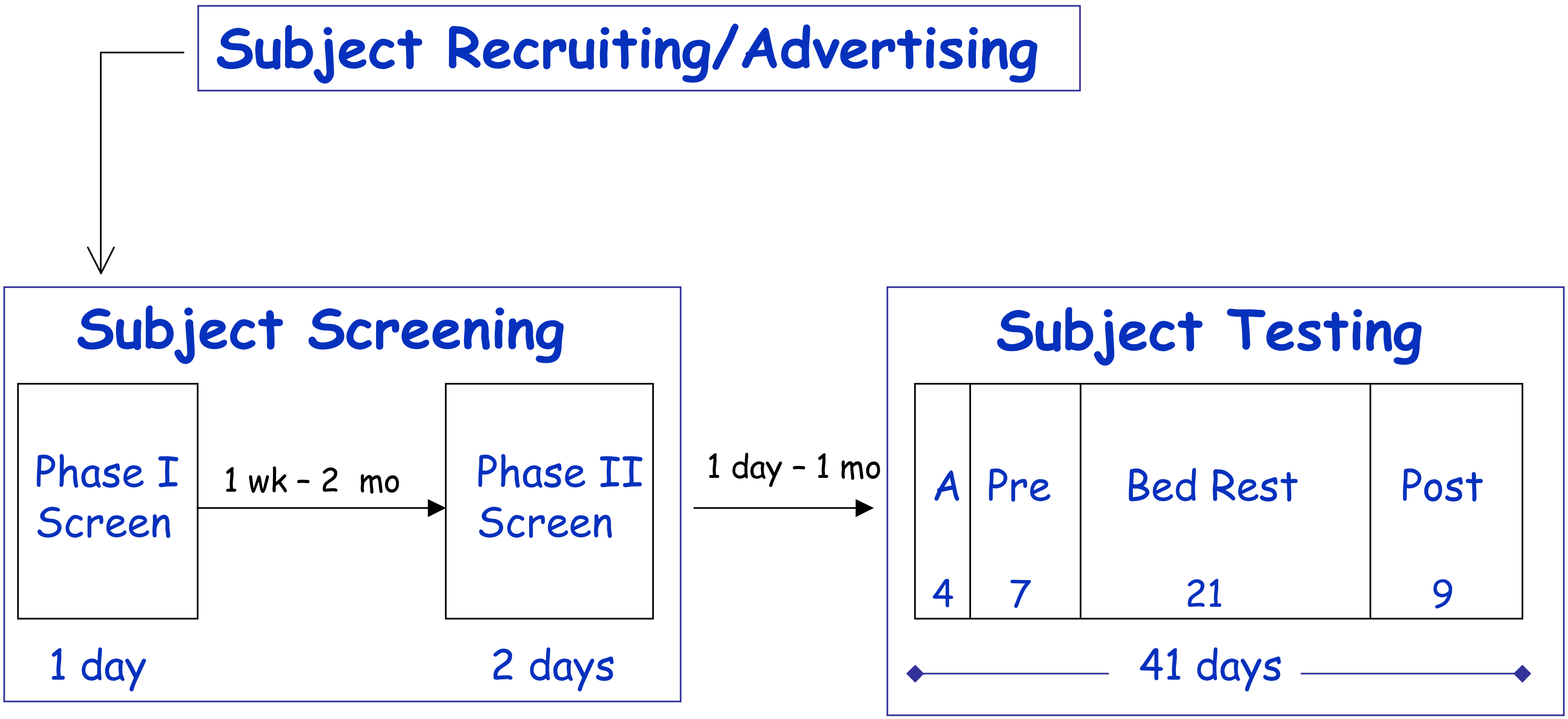


1 g spin* | 1 g stand | 2.5 g spin*

*g-level at feet on 2.5 m radius centrifuge

after Rowell, 1986

Pilot Study Implementation



Pilot Study Investigator Team

PI: W. Paloski (JSC) **Co-PI:** L. Young (MIT)

Bone: A. LeBlanc (BCM), S. Smith & L. Shackelford (JSC)

Muscle: K. Baldwin (UCI), A. Ferrando (UTMB), D. Hagan (JSC)

Cardio: J. Meck & D. Hagan (JSC), J. Evans & C. Knapp (Kentucky), S. Moore (Mt Sinai)

Neuro: L. Young & T. Jarchow (MIT), S. Moore (Mt Sinai), W. Paloski & M. Reschke (JSC), H. Hecht (Mainz)

Nutrition: S. Smith (JSC), A. Ferrando (UTMB), M. Heer (DLR)

Immuno: R. Stowe (UTMB), C. Sams & D. Pierson (JSC)

Psych: A. Holland (JSC), F. Carpenter (JSC)

Biostats: A. Feiveson (JSC), A. Natapoff (MIT)

Clinical/Operational Consultants: J. Jones (JSC), J. Hoffman (MIT)

Pilot Study Subject Screening

General: Air Force Class III (modified)

Bone: DEXA: femoral neck, trochanter, lumbar spine

Muscle: n/a

Cardio: Bruce test w/12 lead ECG, V_{O_2}, centrifuge tolerance

Neuro: balance control (Equitest), centrifuge tolerance

Nutrition: BMI, 6 month history

Immuno: n/a

Endocrine: glucose handling, thyroid, androgen/estrogen

Menses: all women pre-menopausal, no oral contraceptives, no bis-phosphanate therapy

Psych: family & medical history, MMPI-2, 16 PF, NEO-PI-R, clinical evaluation (1 hr)

All test measures required to be within astronaut population norms

Pilot Study Dependent Measures

Bone	DEXA, pQCT, MRI: BMD and morphology	biochemical markers, Ca^{++} balance
Muscle	TVD, fitness, MRI	soleus biopsy: morphology/biochemistry
Cardio	tilt test, tolerance test, V_{O_2}	neuro-endocrine, plasma & segment volumes, ECG spectral analysis
Neuro	balance control	FSR, OCR, SVV, SPP
Immuno		stress markers, viral reactivation, virus-specific T lymphocyte
Psyche	cognitive assessment	
Nutrition	clinical assessment	

NASA Bed Rest Project

Selected PIs
Experiment Protocol
PI-Specific Measures
Analysis / Results

Bed Rest Project Management, Integration, and Support

UTMB GCRC
3-bed facility
(+ 5-FY05 + 5 FY06)
Subject Care
Subject Charts/Records
Nursing Staff
Physician
Storage
Metabolic Kitchen
GCRC Lab

NASA BRP
Psych Support
Subject / Medical Monitors
Subject/Sample Transportation
Bed Rest Std Measures

NASA HTSF
Subject Recruiting
Subject Screening
Subject Test Logs

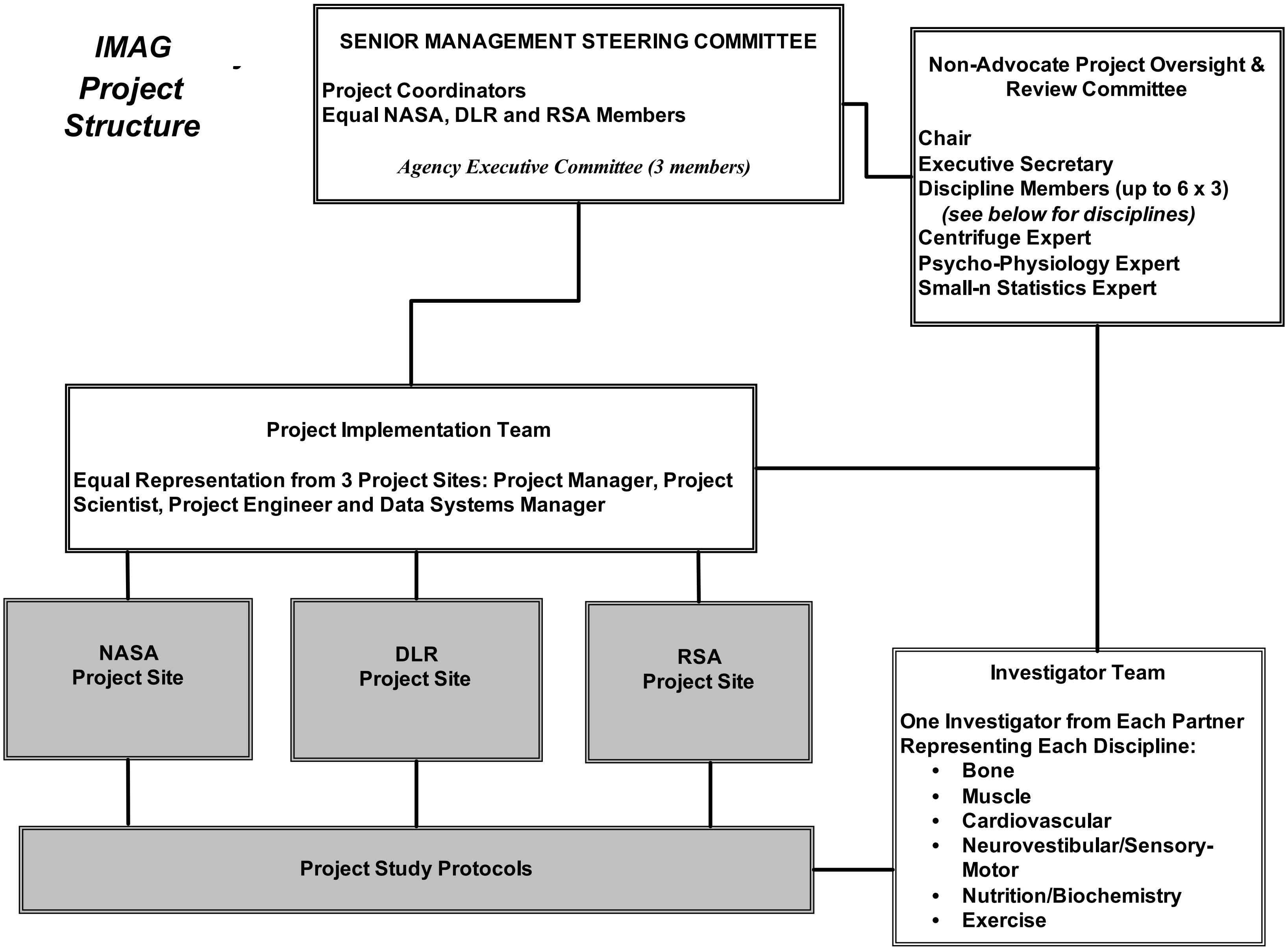
NASA Labs
ITR Data Collection
Lab Test / Analysis
Lab Equipment / Training
Data Archive / Reporting

IMAG Pilot Study Specific Aims

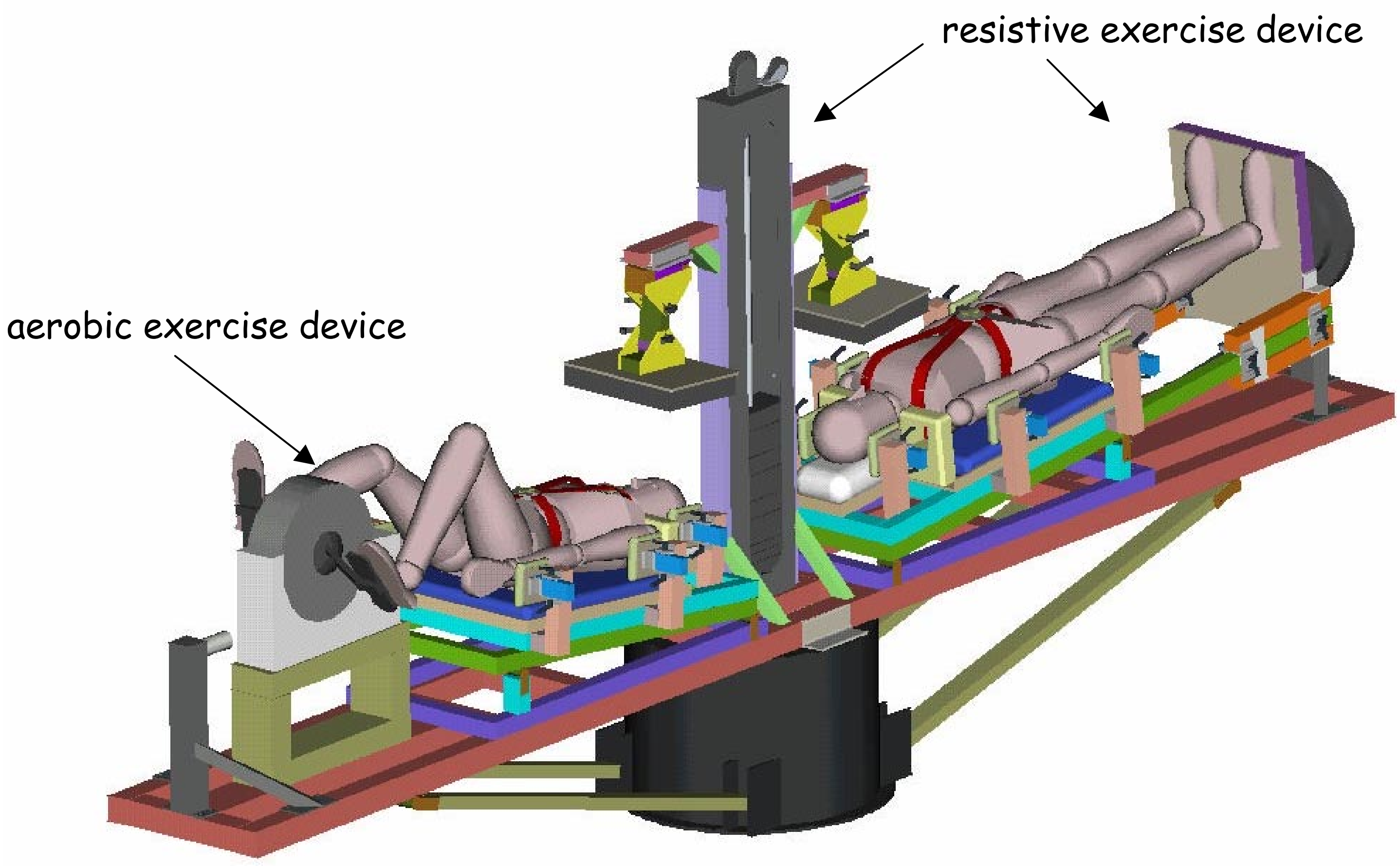
1. Validate the suitability of the proposed dependent measures, subjects, processes, equipment, and procedures for investigating the efficacy of intermittent *AG*, possibly augmented by other countermeasures, in protecting bone, muscle, cardiovascular, and neurological function in deconditioned human subjects, and

2. Obtain data that demonstrate the potential effectiveness of short-radius, intermittent *AG* as a countermeasure to the bone, muscle, and cardiovascular, and possibly neurovestibular deconditioning that occur during three weeks of 6° head down tilt bed rest.

IMAG Project Structure



IMAG Phase 2 Centrifuge



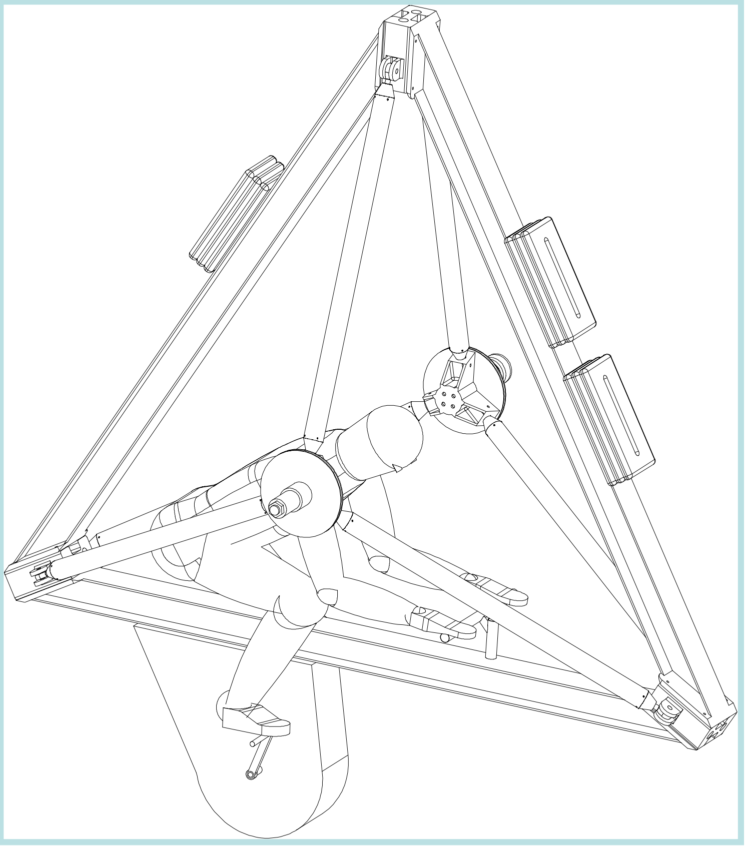
IMAG Phase 3 (Flight) Centrifuge

Artificial Gravity Research Aboard the R2 Mission

The Human Short-Arm Centrifuge for ISS

Flight Experiment Goals:

- Develop and flight test a versatile human short-arm centrifuge facility.
- Demonstrate the feasibility of using centripetal acceleration as gravity replacement therapy during space flight.
- Test the hypothesis that AG plus moderate aerobic exercise will maintain aerobic capacity in crewmembers aboard a 16 day space flight mission.



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- **Animal Studies (Rodent, Rhesus; Ground, CAM)**
  - Larger n, Quicker answers, Lower costs than humans
  - Preliminary results guide human studies

Earth is the cradle of humanity,

but one cannot remain in the cradle forever.

Konstantin Edouardavich Tsiolkovsky