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Artificial gravity is an old concept, having gotten its start in the late in
the 19th century when Konstantin Tsiolkovsky, considered by many to be the
father of the Russian space program, realized that the human body might not
respond well to the free fall of orbital space flight. To solve this problem, he
proposed that space stations be rotated to create centripetal accelerations that
might provide inertial loading similar to terrestrial gravitational loading.
Einstein later showed in his equivalence principle that acceleration is indeed
indistinguishable from gravity. Subsequently, other individuals of note,
including scientists like Werner von Braun as well as artists like Arthur C.
Clarke and Stanley Kubrick, devised elaborate solutions for spinning vehicles
to provide “artificial gravity” that would offset the untoward physiological
consequences of spaceflight.

By 1959, concerns about the then-unknown human responses to
spaceflight drove NASA to consider the necessity of incorporating artificial
gravity in its earliest human space vehicles. Of course, owing in part to the
relatively short durations of the planned missions, artificial gravity was not
used in the early NASA programs. We learned from these early missions that
humans could tolerate short periods of zero-G, but a fear remained that longer
exposures would lead to more profound effects, and that eventually an
exposure threshold would be reached, beyond which crew health, safety, and
performance might be compromised to the point of placing individual
crewmembers or entire missions at unacceptable risk. Therefore, throughout
the 1960s, NASA sponsored many forums to debate the need for artificial
gravity on longer duration human spaceflight missions.

During the 1970s, we learned from the Skylab program that humans
could tolerate many weeks of zero-G exposure without reaching any untoward
thresholds. During the last two decades, we’ve learned from the Mir and ISS
programs that system-specific countermeasures (e.g., resistive and aerobic
exercise emerged) can provide moderately successful physiological protection
for six-month missions in low Earth orbit (LEO). But recently, NASA’s
thoughts have turned to more distant destinations, focusing first on long-
duration stays on the Moon and moving on to 1000-day missions to Mars or
other locations well beyond LEO. These goals have led to a renewed interest
in artificial gravity, stimulating workshops to develop international consensus on the open artificial gravity research issues and engineering studies of feasible designs for spinning transit vehicles.

Physiological deconditioning is not the only factor challenging human space exploration. Psychological factors (e.g., boredom, isolation, small group dynamics), environmental factors (particularly radiation exposure), and logistics (e.g., air, water, and food supplies) will also present increasingly significant challenges as mission durations increase. Each of these factors could potentially limit the duration of future human missions. Therefore, accessible distances will be dictated by the available propulsion systems. To maximize the potential for any given propulsion system, it will behoove space-faring nations to invest in research and development efforts focused on reducing the impact of each of the four areas. Optimal solutions will not only maintain crewmembers fitness-for-duty throughout the mission and protect their long-term health, but will do so with high reliability using minimal mission resources (i.e., mass, volume, crew time).

Because the primary factor affecting physiological deconditioning during spaceflight is the loss of gravitational loading and stimulation, there is little doubt in my mind that the most effective physiological countermeasure would be to bring gravity along, probably in the form of centripetal acceleration. Spinning the vehicle would likely be the most reliable and efficient physiological countermeasure, since it would be passive and omnipresent, would add no mass or volume above the basic vehicle design, and would require energy inputs only during ramp up and down from the desired angular velocity, presumably at the beginning and end of the transit phase of the mission. If designed correctly to minimize the impact of Coriolis accelerations, a rotating vehicle would also have salutary effects on some aspects of psychological deconditioning because many of the cumbersome, inefficient systems required in the galley, waste collection system, sleeping, exercise, and other areas could be eliminated as standard terrestrial designs would suffice. Intermittent, short-radius artificial gravity designs would have fewer advantages during transit, but might be critical during extended sojourns in the hypo-gravity environments of many of the celestial objects targeted for exploration, including Moon, Mars, Mars moons, asteroids, and other destinations, where it would not be useful to remain within a (continuously rotating) habitat throughout the surface stay.

As space agencies seek to undertake human missions to distant destinations, they must inevitably consider artificial gravity designs and the physiological and human factors research necessary to develop optimal artificial gravity prescriptions for their crews. This book should prove to be an invaluable reference to those scientists, engineers, and program managers responsible for future artificial gravity research.
Drs. Clément and Bukley have assembled for the first time in one volume all of the key findings and the key unknowns relevant to designing effective artificial gravity countermeasures. Since many of the chapters were written by today’s leaders in space physiology and artificial gravity research, the book captures well the current state of knowledge of the physiology of artificial gravity and provides good guidance on the critical issues that must be addressed before a practical artificial gravity countermeasure can be realized. It has been a pleasure to collaborate with them on this book. I hope that you, the reader, will benefit from our efforts.

William H. Paloski
Houston, 1 December 2006
PREFACE

Human space exploration has been limited thus far to low Earth orbit and to short visits to the Moon. These missions typically last only a few days to a few weeks, with the exception of extended stays on Mir and the International Space Station. For the short-duration missions, the adverse effects of weightlessness on the human body are minimal. However, once we begin extended exploration of the Moon and beyond, as is currently being studied by many space agencies around the world, mission durations will increase significantly, thus exposing the crews to the detrimental effects of weightlessness. The consequences of long-term weightlessness include undesirable physiological adaptations that impede the ability of astronauts to function efficiently upon the return to an environment with gravity. The more serious of these affects include sensory-motor and cardiovascular deconditioning, orthostatic intolerance, muscular atrophy, and bone demineralization (see Clément 2005, *Fundamentals of Space Medicine*, in this Space Technology Library series).

Countermeasures that reduce the effects of weightlessness have been developed and some are commonly employed. For example, muscular exercise, extra dietary calcium, and other pharmaceuticals can be used to mitigate physiological adaptations to weightlessness. Such countermeasures focus only on certain organ systems and symptoms and most require specially adapted therapeutic equipment. These techniques are time consuming and demand a high degree of individual discipline. Unfortunately, these countermeasures are only partially effective.

Artificial gravity has the potential to fully mitigate the physiological deconditioning that results from long-term exposure to weightlessness. Today’s approach to countering the deleterious effects of microgravity is piece-meal, whereas artificial gravity provides an integrated countermeasure affecting multiple physiological systems. It could replace terrestrial gravity with inertial forces generated by centrifugation or sustained linear acceleration. In fact, many Mars mission designs in the early days of the space program recommended such an approach. Most concepts called for the use of spinning transit vehicles, which were not implemented in part due to technical issues associated with system complexity and cost in mass and energy.

Even though new technologies exist to allow construction of such vehicles, there remain many unknowns as to how humans can adapt to a rotating environment and then re-adapt to a non-rotating environment (e.g., when they arrive on Mars). These human aspects are the primary focus of this book. Recent studies suggest that humans can adapt to high rates of rotation at short radius. Therefore, an alternative to rotating the entire habitat is to
provide a short-radius centrifuge within the habitat and deliver therapeutic doses of artificial gravity. This would result in an overall simpler and more affordable design.

To our knowledge, there is currently no book entirely dedicated to the subject of artificial gravity. Research in this area is only documented in conference proceedings and a few journal articles. Therefore, this book is unique, timely, and addresses artificial gravity from a multidisciplinary standpoint. The first chapters cover the history, fundamental principles, and rationale for using artificial gravity during space missions. Also described are current options proposed for generating artificial gravity, including a short-radius centrifuge contained within a spacecraft. In the subsequent chapters, experts provide recommendations on the research needed to assess whether continuous or intermittent artificial gravity prescriptions (mostly centrifugation) can limit deconditioning of sensory-motor, cardiovascular, and musculo-skeletal systems. These chapters summarize what is known about the effects of micro- and hypergravity in each discipline, and what is still to be learned.

Space research has revealed that plastic changes are induced in multiple physiological systems following exposure to weightlessness. These systems interact with each other, resulting in combined effects. Developing countermeasures for mitigating the deleterious effects of weightlessness, therefore, requires an integrative focus. Three chapters address the interdependences between physiological systems, including the autonomic and immune systems as well as nutritional considerations. In the last chapters special attention is given to medical, psychological, and safety issues related to artificial gravity implementation. Finally, we propose a number of recommendations for additional research.

We have constructed this book in such a way that each chapter stands on its own. Therefore, those who read the book in its entirety will notice a few redundancies. This is intentional so that readers wishing to investigate a specific topic can go to the chapter addressing that subject matter and understand that material in the overall context of artificial gravity research.

It is our hope that the information provided herein will inspire new research in artificial gravity and one day be used in the planning and design of future long-duration space missions.

Gilles Clément and Angie Bukley
Athens, 23 November 2006
ACKNOWLEDGEMENTS

The inspiration for this book was derived from the work of the European Space Agency (ESA) Topical Team on Artificial Gravity. The Topical Team was formed as a result of a proposal submitted to an International Space Life Sciences Research Announcement in November 2004. Dr. Gilles Clément chaired the Topical Team. The group worked together electronically for nearly a year and finally convened in Noordwijk, The Netherlands in November 2005, where much of the content of this book was defined. We sincerely appreciate the inputs that were provided by all the participants in the Topical Team and especially the support provided by ESA.

Other inputs for this book were derived from papers and discussions that occurred during a series of five National Aeronautics and Space Administration (NASA) symposia organized by Dr. Ashton Graybiel and convened between 1965 and 1970 in Pensacola (Florida, USA) on the topic of “The Role of the Vestibular Organs in Space Exploration”. Another milestone was the Workshop on Artificial Gravity organized by Drs. William Paloski and Laurence Young in 1999 in League City (Texas, USA), which was sponsored by NASA and the National Space Biomedical Research Institute. Another primary source of the material in this book originates from the results of an International Academy of Astronautics (IAA) Study Group on the subject of artificial gravity.

The proceedings of all the meetings mentioned above are included in the references following this acknowledgement. We wish to thank all of the people who participated in these meetings for their valuable inputs. This book is a legacy of their work.

The editors are extremely grateful to the authors who wrote selected chapters of this book, some of whom are shown in the photograph below, and especially to Dr. William Paloski for coordinating and co-editing several sections. We also thank Oliver Angerer and Millard Reschke for reviewing the final manuscript.

This book was compiled during Dr. Clément’s stay at Ohio University in Athens, Ohio. His appreciation is extended to the Department of Chemical and Biomolecular Engineering, the Faculty and Staff of the Russ College of Engineering and Technology, and in particular to Dean Dennis Irwin.

Thanks to Mr. Philippe Tauzin, from the Service Commun Multimédia of the Université Paul Sabatier in Toulouse, for his help with some of the artwork. We also appreciate the great work done at NASA and ESA to document, catalogue, and provide access to their archives and multimedia galleries.

Dr. William Paloski provided exceptional contributions to this book. His pioneering research on artificial gravity at the NASA Johnson Space Center
brings together a multidisciplinary team of physiologists, engineers, and physicians and provides a model for future studies.

Finally, thanks to Dr. Harry (J.J.) Blom and to Dr. James R. Wertz who continue to offer us the opportunity to publish in the Space Technology Library series.


*Group photo of the participants in the ESA Topical Team Workshop on Artificial Gravity convened in Noordwijk, The Netherlands from 28-30 November 2005. Participants to this Workshop provided many valuable inputs to this book. From left to right: Eric Groen, Gilles Clément, Oliver Angerer, Angie Bukley, Pierre Denise, Guglielmo Antonutto, Marco Narici, Anne Pavy-Le Traon, Guido Ferreri, Jochen Zange, Floris Wuyts, Bill Paloski, Jörn Rittwegger, Joan Vernikos, and Pietro Di Prampero.*
Contents

Foreword v
Preface ix
Acknowledgements xi

CHAPTER 1: THE GRAVITY OF THE SITUATION 1
Gilles Clément, Angie Bukley, and William Paloski

1 Why Artificial Gravity? 1
2 Mars Mission Scenario 4
3 Detrimental Effects of Weightlessness 7
  3.1 Bone Loss 8
  3.2 Muscle Atrophy 8
  3.3 Cardiovascular Deconditioning 11
  3.4 Sensory-Motor Deconditioning 12
  3.5 Regulatory Physiology 13
  3.6 Human Factors 15
4 Activities on Mars Surface 16
5 Current Countermeasures 19
  5.1 In-Flight Countermeasures 19
  5.2 Research on Countermeasures 22
6 Artificial Gravity is an Integrated Countermeasure 25
7 References 30

CHAPTER 2: PHYSICS OF ARTIFICIAL GRAVITY 33
Angie Bukley, William Paloski, and Gilles Clément

1 Artificial Gravity: What Is It? 33
  1.1 Definition 33
  1.2 How to Generate Artificial Gravity 34
    1.2.1 Linear Acceleration 35
    1.2.2 Mass 36
    1.2.3 Magnetism 36
    1.2.4 Gravity Generator 37
    1.2.5 Centrifugal Force 37
2 Artificial Gravity Generated by Rotation 38
  2.1 Gravity Level 38
  2.2 Gravity Gradient 40
  2.3 Coriolis Force 41
3 Human Factors Considerations 44
  3.1 Gravity Level 44
  3.2 Rotation Rate 45
CHAPTER 3: HISTORY OF ARTIFICIAL GRAVITY  
Gilles Clément, Angie Bukley, and William Paloski

1 Concepts  
1.1 History of Space Travel and Artificial Gravity  
1.2 Science Fiction  
1.3 Formal Studies

2 Experience with Artificial Gravity  
2.1 Flight Animal Experiments  
2.2 Human Space Experience

3 Ground-Based Centrifuge Experiments  
3.1 Long-Radius Centrifugation  
3.2 Short-Radius Centrifugation  
3.3 Human Powered Centrifuge

4 Summary

5 References

CHAPTER 4: PHYSIOLOGICAL TARGETS OF ARTIFICIAL GRAVITY: THE SENSORY-MOTOR SYSTEM  
Eric Groen, Andrew Clarke, Willem Bles, Floris Wuyts, William Paloski, and Gilles Clément

1 Structure and Function of the Sensory-Motor System  
2 Spatial Orientation  
2.1 Visual Orientation  
2.2 Sensory Reinterpretation  
2.3 Perception of the “Vertical”  
2.4 Spatial Disorientation during Piloting

3 Motion Sickness  
3.1 Sensory Conflict Model  
3.2 Centrifuge Induced Sickness  
3.3 Coriolis Induced Sickness

4 Eye Movements  
4.1 Eye Movements during Centrifugation  
4.2 Ocular Counter-Rolling  
4.3 Velocity Storage
### CHAPTER 5: PHYSIOLOGICAL TARGETS OF ARTIFICIAL GRAVITY: THE CARDIOVASCULAR SYSTEM

_Guglielmo Antonutto, Gilles Clément, Guido Ferretti, Dag Linnarsson, Anne Pavy-Le Traon, and Pietro Di Prampero_

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>138</td>
</tr>
<tr>
<td>2</td>
<td>138</td>
</tr>
<tr>
<td>2.1</td>
<td>138</td>
</tr>
<tr>
<td>2.2</td>
<td>139</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
</tr>
<tr>
<td>3.1</td>
<td>141</td>
</tr>
<tr>
<td>3.1.1</td>
<td>141</td>
</tr>
<tr>
<td>3.1.2</td>
<td>142</td>
</tr>
<tr>
<td>3.1.3</td>
<td>143</td>
</tr>
<tr>
<td>3.2</td>
<td>144</td>
</tr>
<tr>
<td>3.3</td>
<td>147</td>
</tr>
<tr>
<td>4</td>
<td>147</td>
</tr>
<tr>
<td>5</td>
<td>148</td>
</tr>
<tr>
<td>5.1</td>
<td>149</td>
</tr>
<tr>
<td>5.2</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>151</td>
</tr>
<tr>
<td>6.1</td>
<td>151</td>
</tr>
<tr>
<td>6.2</td>
<td>152</td>
</tr>
<tr>
<td>7</td>
<td>153</td>
</tr>
<tr>
<td>8</td>
<td>157</td>
</tr>
<tr>
<td>9</td>
<td>159</td>
</tr>
</tbody>
</table>

### CHAPTER 6: PHYSIOLOGICAL TARGETS OF ARTIFICIAL GRAVITY: THE NEUROMUSCULAR SYSTEM

_Mario Narici, Jochen Zange, and Pietro Di Prampero_

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>164</td>
</tr>
<tr>
<td>1.1</td>
<td>164</td>
</tr>
<tr>
<td>1.2</td>
<td>164</td>
</tr>
<tr>
<td>1.3</td>
<td>165</td>
</tr>
</tbody>
</table>
### Contents

<table>
<thead>
<tr>
<th>6</th>
<th>Hypergravity Bone Research</th>
<th>216</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Past Research</td>
<td>217</td>
</tr>
<tr>
<td>6.2</td>
<td>Research Questions</td>
<td>221</td>
</tr>
<tr>
<td>7</td>
<td>References</td>
<td>223</td>
</tr>
</tbody>
</table>

#### CHAPTER 8: INTERACTIONS AMONG THE VESTIBULAR, AUTONOMIC, AND SKELETAL SYSTEMS IN ARTIFICIAL GRAVITY

_Pierre Denise, Hervé Normand, and Scott Wood_

| 1 | Introduction | 233 |
| 2 | Central Vestibulo-Autonomic Pathways | 234 |
| 3 | Vestibular Influence on Cardio-Respiratory Function | 235 |
| 3.1 | Cardiovascular Regulation | 235 |
| 3.1.1 | Animal Studies | 235 |
| 3.1.2 | Studies in Humans | 237 |
| 3.1.3 | Implications for Artificial Gravity | 238 |
| 3.2 | The Respiratory System | 239 |
| 4 | Vestibular Influence on Bone Mineralization | 240 |
| 5 | Vestibular Influence on Hypothalamic Regulations | 242 |
| 6 | Implications for Using Artificial Gravity as a Countermeasure | 243 |
| 7 | References | 244 |

#### CHAPTER 9: INTERACTIONS AMONG ARTIFICIAL GRAVITY, THE AFFECTED PHYSIOLOGICAL SYSTEMS, AND NUTRITION

_Martina Heer, Natalie Baecker, Sara Zwart, and Scott Smith_

| 1 | Introduction | 249 |
| 2 | Energy Intake and Macronutrient Supply | 250 |
| 2.1 | Energy Intake | 250 |
| 2.2 | Protein Supplementation | 252 |
| 2.3 | Insulin Resistance | 253 |
| 3 | Vitamins and Artificial Gravity | 254 |
| 3.1 | Vitamin A | 254 |
| 3.2 | Vitamin K | 255 |
| 3.3 | Vitamin B6 | 256 |
| 4 | Minerals and Artificial Gravity | 257 |
| 4.1 | Calcium and Vitamin D | 257 |
| 4.2 | Phosphorus and Magnesium | 258 |
| 4.3 | Sodium | 259 |
| 4.4 | Potassium | 260 |
| 4.5 | Iron | 261 |
| 5 | Impact of Artificial Gravity on GI-Tract | 262 |
| 6 | References | 262 |
CHAPTER 10: ARTIFICIAL GRAVITY AND THE IMMUNE SYSTEM FUNCTION

Satish Mehta, Brian Crucian, Duane Pierson, Clarence Sams, and Raymond Stowe

1 Effects of Spaceflight
2 Design of the Immune Components of Artificial Gravity Studies
   2.1 Sample Collections
   2.2 Psychological Stress Measures
   2.3 Physiological Stress
   2.4 Immune System Status
      2.4.1 Peripheral Immunophenotype Analysis
      2.4.2 Assessment of T-Cell Function
      2.4.3 Assessment of Intracellular Cytokine Profiles
      2.4.4 Virus-Specific T-Cell Levels and Function
3 Latent Virus Reactivation
   3.1 Epstein-Barr Virus
   3.2 Cytomegalovirus
   3.3 Varicella-Zoster Virus
   3.4 Quantification of Viral Reactivation in Artificial Gravity
4 References

CHAPTER 11: MEDICAL, PSYCHOLOGICAL, AND ENVIRONMENTAL ISSUES OF ARTIFICIAL GRAVITY

Jeffrey Jones, Randal Reinertson, and William Paloski

1 Introduction
2 Space Medicine
   2.1 Environmental Hazards of Spaceflight
      2.1.1 Hypobarism
      2.1.2 Toxic Compounds
      2.1.3 Radiation
      2.1.4 Impact
   2.2 Environmental Hazards Inside the Habitat
      2.2.1 Atmospheric Composition
      2.2.2 Water Chemical Contamination
      2.2.3 Microbial Content
      2.2.4 Thermal Stress
      2.2.5 Noise
      2.2.6 Vibration and Acceleration
   2.3 Psychological Hazards
      2.3.1 Chronobiology
      2.3.2 Isolation
   2.4 Microgravity
   2.5 The Role of the Flight Surgeon
CHAPTER 12: SAFETY ISSUES IN ARTIFICIAL GRAVITY STUDIES

John Byard, Larry Meeker, Randal Reinertson, and William Paloski

1 General Safety Principles 315
1.1 System Safety 315
1.1.1 Hazard Identification and Analysis 316
1.1.2 Hazard Control 317
1.2 Safety Analysis Techniques 318
1.2.1 Hazard Analysis 318
1.2.2 Process Hazard and Operational Analysis 318
1.2.3 Fault Tree Analysis 319
1.2.4 Failure Modes and Effects Analysis 319
1.2.5 Human Factors Safety Analysis 319
1.2.6 Software Safety Analysis 319
1.2.7 Energy Trace Barrier Analysis 319
1.2.8 Sneak Circuit Analysis 320
1.2.9 Cause Consequence Analysis 320
1.3 General Safety Summary 320
2 Hazards in Centrifuge System Design 320
2.1 Mechanical Hazards 320
2.1.1 Sharp Edges and Pinch Points 320
2.1.2 Mechanically Stored Energy 320
2.1.3 Moving or Rotating Parts 321
2.1.4 Touch Temperatures 321
2.1.5 Acoustics 322
2.1.6 High Pressure Systems 322
2.2 Control of Hazardous Energy Sources 323
3 Safety in Centrifuge Design 323
3.1 Structural Design 324
3.2 Drive System 325
3.3 Control System 326
CHAPTER 13: RECOMMENDED RESEARCH

Joan Vernikos, William Paloski, Charles Fuller, and Gilles Clément

1 Introduction

2 Potentials Tools for Investigations

3 Animal Models

3.1 Non-Human Primates

3.2 Rats

3.3 Mice

4 Critical Questions

4.1 Physiological Deconditioning

4.2 Crew Health and Performance

4.3 Other Spaceflight Environmental Factors

4.4 Vehicle and Mission Design

5 Recommendations

5.1 Artificial Gravity as a Multipurpose Countermeasure

5.2 Artificial Gravity Prescription

5.3 Developing Gravity Requirements

5.4 Effectiveness of a Countermeasure

5.4.1 Measures of Effectiveness

5.4.2 Countermeasure Evaluation Methods

5.4.3 Monitoring Technology Requirements

5.4.4 Bed-Rest Study Standardization
Chapter 1

THE GRAVITY OF THE SITUATION

Gilles Clément,\(^1\,^2\) Angie Bukley,\(^2\) and William Paloski\(^3\)

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\(^2\) Ohio University, Athens, Ohio, USA \\
\(^3\) NASA Johnson Space Center, Houston, Texas, USA

Prolonged exposure of humans to a weightlessness environment can lead to significant loss of bone and muscle mass, cardiovascular and sensory-motor deconditioning, and hormonal changes. These adaptive changes to weightlessness present a formidable obstacle to the human exploration of space, particularly for missions requiring travel times of several months or more, such as on a trip to Mars. Countermeasures that address each of these physiological systems separately have shown only limited success. One possible remedy for this situation is artificial gravity because it influences all of these systems across the board.

Figure 1-01. Astronauts returning from long-duration space missions have difficulty standing upright and moving around. Photo courtesy of NASA.

1 WHY ARTIFICIAL GRAVITY?

Ongoing manned spaceflight efforts are now focused on preparing for human interplanetary missions to Mars in the not-too-distant future. These missions will have durations measured in years; therefore, the Mars exploration crews will be at risk of catastrophic consequences should the
systems that provide adequate air, water, food, and thermal control fail. Furthermore, the crews will be exposed to radiation en route as well as on extraterrestrial surfaces that may result in serious health or safety risks. Behavioral issues associated with the prolonged isolation and confinement, and severe physiological deconditioning due to weightlessness\(^1\) are other hazards with which the explorers will face.

Mitigating the harmful effects of prolonged exposure to space radiation and weightlessness is one the most significant challenges that must be addressed to realize the long-duration exploration missions currently envisioned. Given the fact that the astronaut explorers who will undertake these missions will be exposed to these deleterious effects for up to several years while they travel to and from Mars, it is of extreme importance that effective countermeasures\(^2\) are identified, developed, tested, and proven prior to undertaking such challenging missions.

Without the protection of an atmosphere, astronauts will be exposed to high levels of radiation through a steady flux of cosmic particles. Only one year in low-Earth orbit results in a radiation dose that is 10 times that of the annual dose on Earth. Experts predict that the dose of radiation received during a 30-month journey to Mars will amount to about 1,000 times that of the annual dose on Earth, resulting in a high risk of developing chromosomal aberrations in blood lymphocytes and cancer later in the astronauts’ lives. Protective shielding and protective drugs may lower this risks to an acceptable level (Cucunotta et al. 2001).

More immediate physical effects are those induced by prolonged exposure to weightlessness. These include the loss of bone density, muscle mass, and red blood cells; cardiovascular, circulatory, and sensory-motor deconditioning; and changes in the immune system (Figure 1-02). These effects have been noted in astronauts and cosmonauts exposed to weightlessness for durations of significantly less time than those that will be experienced by future explorers of Mars. Body changes that occur after entering microgravity represent normal homeostatic responses to a new environment. The body’s control systems recognize the lack of gravity and begin to adapt to this unique situation, not realizing that the ultimate plan is to return to normal gravity after a transient visit to microgravity. While such reactions by the body may be completely appropriate in the microgravity

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\(^1\) *Weightlessness* is the experience (by people and objects) during freefall, of having zero g-force (0 g) or zero apparent weight. This condition is also known as microgravity, since weightlessness in a spaceship is not perfect.

\(^2\) In a military application, *countermeasures* are systems designed to prevent weapons from acquiring and/or destroying a target. By analogy, in space medicine, countermeasures are systems (mechanical, pharmalogical, procedural) designed to neutralize the hazards of the space environment for astronauts’ health and performance.
environment of flight, they are indeed quite inappropriate for arrival on the surface of another planet or for the return to Earth (see Figure 1-01).

Space biomedical researchers have been working for many years to develop countermeasures to reduce or eliminate the deconditioning associated with prolonged weightlessness. Despite these countermeasures, most astronauts experience problems with balance, orientation, and fainting during the first few days after landing. They also risk muscle tears and bone fractures and therefore must exercise an added degree of caution during their recovery period (White and Arvener 2001).

Given that the purpose of a human mission to Mars is not to go there and simply survive, more effective countermeasures or combinations of countermeasures must be developed to address the effects of long-term exposure to microgravity. Astronauts arriving at Mars in a weakened physical condition with compromised immune systems who can’t manage to ambulate would hardly be able to successfully execute an exploration mission. They would be at risk in the event of a bone fracture, alterations in the heart’s rhythm, development of renal stones, or sensory-motor performance failure during piloting, extra-vehicular activity, or remote guidance tasks. Until the problems associated with microgravity exposure are overcome, such missions cannot be seriously considered.

A number of different countermeasures have been employed in an attempt to mitigate the effects of human exposure to microgravity, generally aiming to stimulate a particular physiological system. Exercise workouts stimulate muscles (and to a lesser extent bones and the cardiopulmonary function), while fluid loading countermeasures target the circulatory responses. While these countermeasures have demonstrated only limited success, they are nevertheless the microgravity countermeasures primarily used on board the International Space Station (ISS) and the Space Shuttle (Sawin et al. 1998)

Artificial gravity is the simulation of the pull of gravity aboard a manned spacecraft by the steady rotation or linear acceleration of all or part of the vehicle (Stone 1973). Artificial gravity represents an alternative approach to addressing the problems of microgravity-induced effects on the human body. Rather than addressing each individual system in a piecemeal fashion, which is only valid if the principle of superposition holds for the combined effect of these interacting subsystems, artificial gravity stimulates all of the physiological systems simultaneously by reproducing the normal Earth gravitational environment. All physical and physiological systems are challenged. Bones are stressed, antigravity muscles are called into action, the otoliths of the vestibular system are stimulated in a manner similar to that on Earth, and the cardiovascular system is similarly stressed. Obviously, artificial gravity cannot address all of the problems associated with long duration spaceflight, in particular that of radiation exposure, altered day/night cycles,
and the attendant psychological issues that will no doubt arise from extended confinement and isolation. It does, however, offer a countermeasure with the possibility to address the debilitating and potentially fatal problems of bone loss; cardiovascular deconditioning, muscle weakening; sensory-motor and neurovestibular disturbances, and regulatory disorders. Because artificial gravity addresses all such systems across the board, it can be considered as an integrated countermeasure (Clément and Pavy-Le Traon 2004).

Figure 1-02. The known adverse affects on human beings of long-term stays in microgravity include bone demineralization, muscle atrophy, and reduction in heart size and plasma volume.

2 MARS MISSION SCENARIO

Mars will be the first nearby world that humans will visit. With its recognizable four seasons, clouds, polar ice caps, mountains, dry riverbeds, and dormant volcanoes, Mars is the most Earth-like planet in our solar system. The greatest potential for human habitation lies on Mars. Although it has a very cold, dry climate, surface temperatures at the equator can reach 26°C during the summer.

Scientists believe that conditions on Mars and Earth were similar billions of years ago. Data from past Mars missions suggest that the planet once had a warmer, wetter climate and abundant liquid water in the form of lakes, rivers, and even oceans during its early history. A detailed exploration
of Mars could potentially provide insight into the past and future of our own planet. We might also learn if Mars could sustain self-sufficient colonies that might prove to be a lifeboat for humanity’s survival in the event of some global calamity. Finally, exploring the planet could create new commercial opportunities and sources of income.

Robotic exploration missions have already provided detailed studies of the planet, located vital sources of water, analyzed soil samples, and identified the best landing sites. At the time this book is being written, the Mars Exploration Rovers Opportunity and Spirit are still exploring small patches of Mars on opposite sides of the planet. NASA and ESA are planning additional missions slated to land at various locations on Mars. These feature mobile or stationary landers equipped with robotic arms for exploration. The little Mars exploring robots are amazing pieces of engineering and have many discoveries left to make. However, they do have their limitations. It took Opportunity 56 days to explore a 20-meter crater. A year was required for Spirit to travel two kilometers, something an astronaut or a more capable robot could perform in a couple of hours.

Although robots will always be a required component of any exploration missions, humans are able to go a little further, wonder what’s over the horizon, and explore areas that the rovers might not be able to reach. Astronauts will drive for kilometers across the planet’s diverse terrain in advanced roving vehicles equipped with specialized tools, drills, and analytical instruments. Much of their time will be spent searching for water and past and present evidence of Martian life forms, as well as conducting a wide range of scientific activities that cannot be accomplished by robotic exploration.

The human explorers must also be shielded from harmful radiation while traveling in their spacecraft and when on the Red Planet’s surface. And because the gravity on Mars is only 0.38 g, it is possible that this is not sufficient for counteracting the detrimental effects of microgravity on their body functions experienced during the journey to Mars. Their survival in such an inhospitable environment will be solely dependent on their combined expertise, specialized skills, available equipment, and countermeasures. When unexpected problems and challenges arise, as they undoubtedly will, the astronauts will be required to solve them with little or no help from Earth. Radio communications with mission controllers will be difficult because of the transmission time delay between Mars and Earth. Depending on Mars’s distance from Earth, which can range from 75 to 350 million km, radio signals from the planet can take anywhere from 5 to 20 minutes to reach Earth.

No one knows how many billions of dollars a human mission to Mars will eventually cost, and the enormous financial burden must necessarily be shared by many nations. The epic endeavor will be far more dangerous and technically difficult to accomplish than the human missions to the Moon that
Artificial Gravity

occurred over four decades ago. The Moon is only 350,000 km away. If an Apollo 13–type disaster were to happen, the astronauts would not be able to return again to Earth.

The urge to explore and natural curiosity are inherent human characteristics that will eventually inspire us to overcome the challenge of sending humans to Mars. The underwater world would not have been so appealing without the visionary human touch of Jacques Cousteau. Thanks to the vision of advocates for human Mars missions, realistic scenarios have been proposed. Since Wernher von Braun first sketched out his Mars Project in 1953, a succession of designs and human mission profiles have been seriously studied in the United States and the Soviet Union/Russia. Comprehensive reviews of Mars expeditions projects are available on the Internet (http://www.astronautix.com/craftfam/martions.htm, retrieved 21 April 2005) and in Portree (2001). The most recent studies of potential Mars mission scenarios include the Paine’s Report on Pioneering the Space Frontier (Paine 1986), Ride’s Report of a Mars Exploration Plan (1987), NASA 90-Day Study Mission (Cohen 1989), NASA Mars Evolution and Space Exploration Initiative studies (Stafford 1991), Robert Zubrin’s Mars Direct approach (Zubrin 1991), NASA’s Design Reference Missions (Hoffman and Kaplan 1997), and the latest NASA’s Vision for Space Exploration (2004) and ESA’s Aurora Programme (Bonnet and Swings 2004).

Historically, proposed scenarios for human missions to Mars have fallen into two categories: conjunction-class and opposition-class. Conjunction-class missions are characterized by low speed transits followed by a long, roughly 500-day, stay on Mars before returning to Earth. The long stay is required because by the time the ship has arrived at Mars, the Earth has traveled too far around the sun to be overtaken on a return trip (Figure 1-03).

Opposition-class missions usually entail faster transits, higher delta-V braking requirements upon arrival, and far shorter stays of roughly 30 to 90 days on Mars. The typical total trip time for such a mission will be approximately 430 days. Often, an opposition-class mission will necessitate the transfer ship crossing inside the orbit of Venus upon return to catch up with the Earth.

As this book is written, a definite timetable for space exploration has not been established. The ultimate time of transit to Mars and back is uncertain because of the undetermined nature of the propulsion system to be employed. Nevertheless, the Mars mission scenario we refer to in this book is a conjunction-class type mission, with an Earth-Mars transit time of about six months, Mars surface stay of about 18 months, and a six-month return flight. Hence, a total mission duration of about 30 months. This scenario is not based on any single specific mission architecture. It reflects the best assessment that can be made at this time concerning the possibility of an extraterrestrial
venture. Despite these uncertainties, the authors of this book believe their findings and recommendations regarding the most important health issues facing human exploration, and the potential of artificial gravity as a countermeasure, would apply independent of mission scenario.

Figure 1-03. During the past several years, several meetings have re-examined potential Mars mission scenarios (Hoffman 1997). This drawing illustrates one feasible scenario for a human mission to Mars. Total mission time is 905 days away from Earth. This conjunction class mission profile includes a 180-day transit to Mars, a 545-day stay on the surface, and a 180-day return flight.

3 DETRIMENTAL EFFECTS OF WEIGHTLESSNESS

The effects of the space environment on the human body are well documented. For a comprehensive review, the reader is invited to consult other books in this Space Technology Library series, including Space Psychology and Psychiatry by Kanas and Manzey (2003) and Fundamentals of Space Medicine by Clément (2005). Artificial gravity cannot solve the critical problems associated with radiation exposure, isolation, confinement, and reliability of life support systems. However, it can deal with the detrimental effects of long-duration exposure to weightlessness. These effects are reviewed here, with an emphasis on the health and operational issues facing human exploration missions.
3.1 Bone Loss

Bones are living tissue, constantly being strengthened by dietary calcium extracted from the blood and destroyed by returning calcium to the blood for excretion. Bone maintenance requires a compressive load along the axis of the bone coupled with some high-force impulsive loading. In the absence of these loads that are normally provided by gravity and walking, the major bones that support body weight begin to deteriorate. As a result, a net loss of body calcium occurs, independent of the amount taken in with food or supplements.

The long bones in the legs and the vertebrae lose mass and strength during prolonged bed rest. Similarly, a loss of bone mineral and its excretion are observed in humans during spaceflight. Calcium is lost at a rate of about 1% per month, and the losses are reflected in the density and mass of weight-bearing bones. The rate of calcium loss is not reduced by vigorous exercise. Along with the calcium loss is also a loss of phosphorus. An increase in urinary hydroxyproline, which is a major component of the protein collagen that strengthens the bone, shows that there is a corresponding deterioration of the bone matrix. The increased blood levels of calcium lead to further concern about possible deposition of calcium in the kidneys or other soft tissues. In weightlessness bone resorption decreases slightly, but bone formation decreases more severely (Leblanc et al. 2000).

These changes account for the net decrease in bone mass, especially in the weight-bearing bones, during spaceflight. Unless the process reaches a plateau, which has not been observed during missions of up to 14 months duration, a 40% decrease in bone mass might occur for a spaceflight lasting two years. Such a decrease in bone mass increases the risk of fracture and might severely alters the ability of the bone to repair itself. Bone loss represents a serious danger to astronauts, especially during exposure to the stresses of re-entry after a long period of weightlessness.

Bone mass changes continue for up to six months after landing (Vico 2000). Consequently, even after arriving on the Mars surface, astronauts may continue to lose bone mass. If it turns out that the Mars gravity level of 0.38 g is not enough to prevent further bone mass deterioration, astronauts returning from a 30-month mission to Mars will possibly suffer severe osteoporosis. While this bone loss is similar in some ways to osteoporosis observed on Earth, pharmacological countermeasures have not yet been shown to be effective in space. Similarly, the effect of exercise in microgravity has not resulted in minimization of bone loss.

3.2 Muscle Atrophy

Muscles are adaptable tissues. Increase the load on them by lifting weights or other types of exertion, and they grow larger and stronger. Reduce
the load by lying in bed or living in microgravity, and they grow smaller and weaker. When a muscle is loaded, its fibers begin a series of intracellular signaling steps. Genes within the cell nucleus make ribonucleic acid (RNA), which synthesizes proteins that make up muscle fiber. Lifting weights activates the expression of these proteins, which accumulate and enlarge the muscle fibers. Microgravity has the opposite effect. It reduces the load that gravity naturally places on muscles, interrupting protein synthesis so that fibers begin to atrophy. This loss of muscle mass contributes to reduced skeletal muscle strength when astronauts return to Earth.

Very significant losses of muscle strength, muscle volume, and total body weight are noted during spaceflight. Muscles that manifest the most significant changes are the major muscle groups in the legs and back that work against Earth’s gravity to support body weight.

These changes represent the actual breakdown of muscle tissue due to its disuse in weightlessness and a reorganization of the properties of the muscle fibers, which are the primary muscle constituents. Only 14 days in microgravity may cause muscle fiber atrophy of as much as 30% (Edgerton et al. 1995). As a result, the muscle generates less force and power. Muscle fibers are of two main types: “slow” fibers that work against gravity to maintain erect posture and “fast” fibers that are involved in rapid, high power movement such as jumping and sprinting. Because slow muscle fibers are the primary anti-gravity effectors, they are affected the most in weightlessness because they are not working against any load. In fact, after long-term exposure to microgravity, the slow muscle fibers begin to behave more like fast fibers when subjected to an external load. Specifically, they contract more rapidly, making them more adapted for rapid bouts of sprinting than for long-term standing or walking. However, they tire quickly.

Studies reveal that about 15-20% of the slow fibers in a thigh muscle convert to fast fibers during a 14-day spaceflight. With longer flights, the degree of fiber switching from slow to fast might increase. A direct consequence of this “reprogramming” of muscle fibers is a decrease in endurance as a function of time in flight, which could have a serious impact on human performance. Furthermore, fast fibers are more vulnerable to injury during contraction. Another matter of concern is the fact animal studies showed that muscle fiber regeneration is less successful in space.

After spaceflight astronauts experience muscle weakness, fatigue, faulty coordination, and delayed-onset response. Muscle atrophy also causes soreness as damaged muscles tear while readjusting to Earth’s gravity. Exercise workouts help astronauts fight back. Historically, U.S. and Russian astronauts have relied on aerobic exercises, primarily pedaling a cycle ergometer (an exercise bike) and running while tethered to a treadmill (Figure 1-04). Unfortunately, aerobic exercises are designed to condition the cardiovascular system rather than apply loads systematically to a wide range
of muscles. Cycling, for example, applies a good load to the upper leg but not the lower leg or back.

Different types of exercise are required to build strength and resistance to fatigue and injury. Any microgravity exercise routine must maintain not only muscle mass and strength, but also the right mix of proteins to balance fast-twitch muscle power with slow-twitch muscle endurance. On Earth, strength-training programs typically combine isotonic and isometric resistance exercises: high-intensity isotonic motions shorten and lengthen muscles (for example, lifting and lowering a dumbbell), and isometrics fully contract muscles without movement (for example, pushing against a doorway). Theoretically, both types of exercise could potentially reduce muscle atrophy in microgravity (Di Prampero et al. 1996). Experiments with rats, however, suggest that isometrics may protect slow fibers better than isotonics because slow fibers develop very little force during relatively fast isotonic motions.

Yet despite rigorous exercise, astronauts return to Earth shockingly weaker than when they left. Exercise alone has not prevented muscle wasting during spaceflight. The ideal microgravity exercise program therefore remains to be defined.

Figure 1-04. Left: Astronauts exercising on the treadmill (left) and on the cycle ergometer (right) on board the ISS. A vibration isolation system reduces the vibration transferred from the devices to the Station structure during exercise. Photos courtesy of NASA.