EXERCISE PROTOCOLS DURING SHORT-RADIUS CENTRIFUGATION FOR ARTIFICIAL GRAVITY

by

JESSICA LEIGH EDMONDS

B.S. Mechanical Engineering, Northwestern University, 2003
B.A. Integrated Science, Northwestern University, 2003
S.M. Aeronautics and Astronautics, Massachusetts Institute of Technology, 2005

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY IN AEROSPACE BIOMEDICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2008

© Massachusetts Institute of Technology
All rights reserved

Signature of Author

Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
May 23, 2008

Accepted by

Professor David L. Darmofal
Associate Department Head
Chair, Committee on Graduate Students
EXERCISE PROTOCOLS DURING SHORT-RADIUS CENTRIFUGATION FOR ARTIFICIAL GRAVITY

by

Jessica Leigh Edmonds

DOCTOR OF PHILOSOPHY IN AEROSPACE BIOMEDICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Certified by

Laurence R. Young, ScD
Apollo Program Professor of Astronautics
Professor of Health Sciences and Technology
Massachusetts Institute of Technology
Thesis Supervisor

Accepted by

Roger G. Mark, MD, PhD
Distinguished Professor of Health Sciences and Technology
Professor of Electrical Engineering and Computer Science
Massachusetts Institute of Technology

Accepted by

Lars Oddsson, PhD
Director of Research
Sister Kenny Research Center
Sister Kenny Rehabilitation Institute

Accepted by

Thomas Jarchow, PhD
Research Affiliate
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
EXERCISE PROTOCOLS DURING SHORT-RADIUS CENTRIFUGATION FOR ARTIFICIAL GRAVITY

Jessica L. Edmonds

Abstract

Long-duration spaceflight results in severe physiological deconditioning, threatening the success of interplanetary travel. Exercise combined with artificial gravity provided by centrifugation may be the comprehensive countermeasure needed to prevent such deconditioning. The aims of this study were (1) to characterize the physiological responses to longitudinal g-gradient and high g-levels during short-radius centrifugation, and (2) to quantify the fitness benefits of an eight-week exercise program on a short-radius centrifuge.

In the first experiment, we utilized a tilting short-radius centrifuge to investigate heart rate, blood pressure, and calf volume responses to high g-level and g-gradient centrifugation with and without light exercise (stepping in place). All measures increased significantly with increasing g-level and increasing g-gradient, but these effects were reduced significantly when the subject stepped in place. In the second experiment, we quantified the effectiveness of an eight-week exercise program using a stair-stepper and resistive arm bands on a horizontally-rotating short-radius centrifuge. Healthy, previously sedentary subjects exercised at a constant heart rate three times per week for eight weeks, and underwent measurements to test aerobic capacity and endurance, strength, and body composition at weeks 0, 4, and 8. Eight subjects successfully completed 24 exercise sessions with little or no discomfort. After eight weeks of exercise, we found significant improvements in aerobic capacity (increased work rate for a given heart rate, increased stepping endurance), muscular strength (increased number of push-ups), and body composition (decreased leg fat percentage, increased pelvic bone mineral content).

Stepping in place significantly reduced the physiological responses to increasing g-level and g-gradient, suggesting that subjects may be able to better tolerate exposure to high-g centrifugation if they exercise. Further, an eight-week exercise program using a stair-stepper on a short-radius centrifuge resulted in improvements to aerobic capacity, strength, and body composition. These two studies demonstrate the feasibility and benefits of exercise in an artificial gravity environment.

Thesis Supervisor: Laurence R. Young, ScD
Title: Apollo Program Professor of Astronautics
Professor of Health Sciences and Technology

Supported by: NASA International Multi-Disciplinary Bedrest Study (grant #NNJ04HD64G), NASA Graduate Student Researchers Program (grant #NNX06AH21H), Zonta International Amelia Earhart Fellowship, and AIAA John Leland Atwood Fellowship.


Acknowledgements

This work would not have been possible without the support of:

- NASA International Multi-Disciplinary Bedrest Study (grant #NNJ04HD64G)
- NASA/Johnson Cooperative Agreement (grant #NNJ04H103A)
- NASA Graduate Student Researchers Program (grant #NNX06AH21H)
- Zonta International Amelia Earhart Fellowship
- AIAA John Leland Atwood Fellowship

First and foremost, I would like to thank my thesis committee. Larry Young: thank you for allowing me to come up with ideas independently, while supporting me intellectually. You have a wonderful talent for allowing your students freedom of thought, and still keeping them on the right track. Thank you for your years of mentorship. Roger Mark: thank you for your patience and instruction in cardiovascular physiology. You spent many hours that I’m sure you didn’t have, and were remarkably tolerant of my endless questions. I also appreciate your very careful review of my thesis – going so far as to bring it right to my door on a Saturday morning! Lars Oddsson: thank you for your practical ideas when it came to the implementation of an exercise program. We were very lucky to have you in the area (for a while, anyway!) – thank you for your independent instruction in the field of exercise physiology. Last but definitely not least: Thomas Jarchow, thank you for being the hole-drilling, paper-editing, math-checking, advice-giving friend and mentor that I needed for many years. Also thank you to Erika Wagner and Paul DiZio for serving as readers of this thesis.

Special thanks to the other faculty and staff of the Man-Vehicle Laboratory. Dava Newman: thank you so much, for truly caring about my well-being, financially supporting me more than once, and being a wonderful role model and mentor. If I ever decide to pursue teaching, it is in no small part due to you. Jeff Hoffman: what an honor to have an astronaut right upstairs – and a congenial and approachable one at that! Thanks for your teaching, your space stories, and being someone that we can all look up to. Chuck Oman: you have been an excellent lab directory in the years I’ve been here, thank you for being supportive and enthusiastic about my project and progress. Liz Zotos: thanks a million for all of the (million) things I’ve asked for, panicked about, complained about, whatever – you’ve been fantastic, and I’ll miss having someone to chat with by the mailboxes! Alan Natapoff: thank you for your many hours of instruction and advice in all things statistical, as well as our many conversations not related to the numbers. And Andy Liu: thanks for never being too busy to give help, or even walk a mile to help me print out a poster.

To the students of the MVL: you are the best thing about being here. I can’t imagine what it will be like to work in the “real world” after so many years with you. Special thanks to (as Erika puts it, the “W” in MVL): Erika Wagner, my travel partner, shopping partner, networking advisor, and even shoulder and ear; Jessica Marquez (I miss you! Why can’t NASA be in Boston?); Kristen Bethke (what are the chances we’d both be here?); and Leia Stirling (we did it! So glad we were in it together). Also thanks to a few other “old-timers”: Chris Carr (I still look up to you, as I did my first day here!); Phil Ferguson (and Ally, and Wendy – miss you guys!); David Benveniste (the Muddy never was quite the same after you left); and Dan Judnick, who finally got me to watch Star Wars. Finally, special thanks to my officemates, who have earned me the multi-year title of “Coolest Office”: Ian Garrick-Bethel and Sophie Adenot, who started it all off; Paul Elias and Jeremie Pouly, thanks for all the cockroach-striking memories; Scott Sheehan and Jaime Mateus, you two probably made me laugh more than was healthy for an MIT nerd, and I really don’t know what I’m going to do when I get assigned to an officemate who doesn’t insult me; and finally Doug, thanks for teaching me Irish.
Years of graduate work are only possible with an amazing support network of friends. Lauren and Carolyn, thank you for being the such wonderful friends and roommates – I’ve been so lucky to have you. Dominika, it’s been really fun to have been with you for so many events in your life, from sharing an apartment through your marriage and more. Leigh and Matt Albrecht, so great to have some non-MIT friends from way back when! Geoff and Kate Huntington, you guys were a blast! Thanks for the memories, and thanks for introducing me to Becca (hi Becca, thanks for the parties and everything else!) Also thank you to all the wonderful friends I’ve me through the Triathlon Club, and through Sidney-Pacific. And of course, thank you to the Sargent Girls, none of whom will ever see this, but you guys are the best, and now you’re having babies and owning cats and buying houses and growing up . . . hold on, I’ll get there soon ☺.

Thank you to my family, without whom I really couldn’t have done any of this. Mom, Dad – I’m afraid the invention of cell phones probably took away about three hours a week for you, based solely on my phone calls. Thank you for championing me, every step of this long journey. Whatever happens from here on out – please know that you are ultimately the ones who have gotten me here. Joe, it’s been great to have you visit me, to visit you, and to enjoy this “being grown-up” thing together, let’s keep it up. And Chris and Lachie, the hardest thing about being in Boston is not being with you. Here, have a thesis to remember me by (hee hee hee).

And to my future family (Kevin): you have been the best part of my day, ever since you asked me to join you for a drink at the Muddy. Thank you for the countless laughs and mischief, the weekend trips and the evening errands, the motorcycle rides and the skiing, the TV-watching nights on the couch, the kielbasa, the grilling out, and everything it took to remind both of us that there are more important thing that big old theses. And especially, thanks for deciding to keep me! Can’t wait for what’s next.

Biography

Jessica Leigh Edmonds was born and raised in Glenview, Illinois. From 1998-2003 she attended Northwestern University, where she worked as an undergraduate research assistant with Professor Mark Robinson in the Department of Geological Sciences. Her work allowed her to present a poster at the 2003 Lunar and Planetary Science Conference, and at graduation, she received the Geological Sciences award for “Best Undergraduate Research by a Non-Major”. In addition to this research, Jessica participated in the NASA Academy at Goddard Space Flight Center (summer 2000) and the Langley Aerospace Research Summer Scholars Program (2001).

Jessica began her graduate work at MIT in September of 2003 in the Department of Aeronautics and Astronautics, working in the Man-Vehicle Laboratory under Professor Laurence Young. She became interested in the concept of combining exercise with artificial gravity, and spent much of her first two years of graduate school building the infrastructure to support an exercise device on the centrifuge. Her experimental work took her to Antwerp, Belgium, where she collaborated with European Space Agency researchers using their Short-Arm Human Centrifuge. She also performed approximately a year of experiments using the MIT Short-Radius Human Centrifuge. Jessica has presented her graduate work at the Bone Loss During Spaceflight Conference (2005), the International Society for Gravitational Physiology (2007), the International Astronautical Congress (2007), the AIAA Aerospace Sciences Meeting (2008), and the Aerospace Medical Association Annual Meeting (2008). She has received the third place for her research in the regional New England AIAA student conference (2005), and holds fellowships from NASA (Graduate Student Researchers Program, 2006-2007), Zonta International (Amelia Earhart Fellowship, 2007), and AIAA (John Leland Atwood Award, 2007).
# Table of Contents

Abstract ........................................................................................................................................... 5  
Acknowledgements ............................................................................................................................ 7  
Biography ......................................................................................................................................... 8  
Table of Contents ............................................................................................................................. 9  
Introduction ..................................................................................................................................... 11  
  1.1 Motivation .................................................................................................................................. 11  
  1.1 Hypotheses and specific aims ................................................................................................. 12  
  1.2 Thesis outline ............................................................................................................................ 13  
  1.3 Contributions ........................................................................................................................... 14  
Background ....................................................................................................................................... 17  
  2.1 Spaceflight related physiological deconditioning ............................................................... 17  
    2.1.1 Musculoskeletal system .................................................................................................. 18  
    2.1.2 Cardiovascular ............................................................................................................. 19  
    2.1.3 Neurosensory changes ................................................................................................. 25  
  2.2 Current countermeasures ......................................................................................................... 26  
    2.2.1 Exercise ....................................................................................................................... 27  
    2.2.2 Pharmaceuticals .......................................................................................................... 33  
    2.2.3 Lower Body Negative Pressure .................................................................................. 34  
  2.3 Artificial gravity ....................................................................................................................... 35  
  2.4 Artificial gravity and exercise ................................................................................................. 36  
  2.5 Summary .................................................................................................................................. 39  
Experiment 1: The effect of light exercise on the physiological response to a gravity gradient ... 41  
  3.1 Introduction .................................................................................................................................. 42  
    3.1.1 Hypotheses ...................................................................................................................... 45  
  3.2 Methods ..................................................................................................................................... 47  
    3.2.1 Hardware ........................................................................................................................ 47  
    3.2.2 Experimental protocol ................................................................................................. 49  
    3.2.3 Analysis ......................................................................................................................... 51  
  3.3 Results ....................................................................................................................................... 52  
    3.3.1 Right calf volume ........................................................................................................... 54  
    3.3.2 Heart rate ....................................................................................................................... 59  
    3.3.3 Arterial blood pressure at heart level ......................................................................... 61  
Experiment 2: Effectiveness of stair-stepping during centrifugation .............................................. 63  
  4.1 Introduction .................................................................................................................................. 63  
    4.1.1 Hypotheses ...................................................................................................................... 64  
  4.2 Methods ..................................................................................................................................... 65  
    4.2.1 Subjects .......................................................................................................................... 65  
    4.2.2 Experimental protocol ................................................................................................. 66  
    4.2.3 Data post-processing ..................................................................................................... 80  
    4.2.4 Statistical analysis ......................................................................................................... 82  
    4.2.5 Pilot experiment ............................................................................................................ 82  
  4.3 Results ....................................................................................................................................... 84  
    4.3.1 Exercise sessions ............................................................................................................ 85
4.3.2 Aerobic changes ................................................................. 86
4.3.3 Strength changes .............................................................. 90
4.3.4 Body composition ............................................................. 92
4.3.5 Other effects and non-effects ............................................ 95
4.3.6 Exit surveys .................................................................... 95
Discussion ................................................................................. 97
5.1 Experiment 1: The effect of light exercise on the physiological response to a gravity gradient .................................................... 97
  5.1.1 Heart rate and blood pressure responses .......................... 98
  5.1.2 Right calf volume responses .......................................... 99
  5.1.3 The effect of stepping in place ....................................... 100
  5.1.4 Off-axis accelerations ................................................... 101
  5.1.5 Short- vs. large-radius centrifugation ............................. 102
  5.1.6 Summary ..................................................................... 105
5.2 Experiment 2: Effectiveness of stair-stepping during centrifugation ................................................................. 105
  5.2.1 Effectiveness of exercise sessions .................................. 105
  5.2.2 Variability in fitness responses ...................................... 108
  5.2.3 Comparison with upright stepping ................................ 108
  5.2.4 Stair-stepping as an exercise modality ......................... 114
  5.2.5 Rehabilitation applications .......................................... 116
5.3 Recommendations ............................................................... 116
Conclusion ................................................................................ 119
  6.1 Summary of major findings ............................................... 119
    6.1.1 Hypothesis 1 .............................................................. 119
    6.1.2 Hypothesis 2 .............................................................. 120
    6.1.3 General observations ................................................ 122
  6.2 Future work ...................................................................... 123
  6.3 Applications ..................................................................... 123
References ................................................................................. 125
Appendix A: Centrifuge hardware development .......................... 135
Appendix B: Considerations for a centrifuge on a spacecraft ........ 147
Appendix C: Informed consents ................................................. 165
Appendix D: Individual subject data, Experiment 1 ..................... 183
Appendix E: Advertising and health forms, Experiment 2 ............ 201
Appendix F: Thesis defense slides ............................................. 209
Chapter One

Introduction

1.1 Motivation

The physiological problems that occur during and after long-duration spaceflight are in large part due to adjustments of systems that have evolved in Earth’s gravity. The weightless environment requires less energy expenditure on average, resulting in a change in function. Bone loss is a well known problem upon return to Earth, as are losses of muscle strength and mass [1, 2]. Cardiovascular deconditioning occurs due to the lack of hydrostatic pressure gradient along the body, and the resulting lowered response of the control mechanisms [3]. However, the body is only responding to its environment, and acting in an appropriately plastic manner, by adapting to this new, weightless environment.

Unfortunately, this adaptation is undesirable for a long-duration spaceflight to a destination with a gravity environment (such as Mars or return to Earth), because the body will again need to function in a gravity field upon arrival. Therefore, the current goals of the human spaceflight program require a detailed understanding of the physiological response to weightlessness; long-duration (6 months or greater) interplanetary spaceflight will take unprecedented tolls on the bodies of the crewmembers. The international community (in particular, Russia and the U.S.) has conducted missions of up to 438 days duration on Mir and the International Space Station (ISS). It is evident from these long-duration spaceflights that, if astronauts are to maintain enough physical conditioning to safely and productively perform exploration and science missions on the surface of another planet, sufficient countermeasures will be needed.
EXERCISE PROTOCOLS DURING SHORT-RADIUS CENTRIFUGATION FOR ARTIFICIAL GRAVITY

We must attempt to formulate countermeasures for spaceflight that will maintain high enough fitness levels for subjects to function in a gravity environment. Current exercise countermeasures have not sufficiently maintained these fitness levels [4], in part due to the systemic difference between weightless (externally loaded) exercise, and Earth-based, gravity-environment exercise. Here we explore the possibility of combining short-radius artificial gravity and exercise, which allows for a more similar exercise environment to Earth-exercise, and may result in higher levels of effectiveness. Artificial gravity provided by centrifugation is considered to be a feasible and potentially useful countermeasure to physiological deconditioning induced by long-duration exposure to microgravity [5-12]. Artificial gravity provided by centripetal acceleration is produced according to the equation:

$$AG = r\omega^2$$

Equation 1

where $AG$ is artificial gravity, $r$ is the radius of the centrifuge, and $\omega$ is the rotation rate.

1.1 Hypotheses and specific aims

The purpose of this thesis is to explore the feasibility and effectiveness of exercise in artificial gravity, by characterizing the effect of exercise in high g-level and high g-gradient environments, and by identifying the fitness benefits of exercise on a centrifuge over a period of eight weeks. Artificial gravity is a promising countermeasure because, unlike current exercise and pharmaceutical approaches, which merely treat the symptoms of weightlessness, artificial gravity removes the cause of the deconditioning. In addition, we can exploit the Earth-like acceleration environment of artificial gravity to perform normal exercise. We postulate that a combination of exercise with artificial gravity is a thorough and effective countermeasure to many of the physiological problems associated with spaceflight.

A concern is that a deconditioned astronaut, after some time in space, would experience orthostatic intolerance and, ultimately, syncope, when on the centrifuge, due to altered autonomic and effector responses to longitudinal acceleration. It has been shown that repetitive leg exercise on the centrifuge assists in the venous return mechanism (venous “pumping” [10]) that could allow the astronaut to tolerate artificial gravity, perhaps even at levels greater than 1-g.
**Hypothesis 1.** Exercise during centrifugation will attenuate heart rate, blood pressure, and calf volume increases due to increasing g-levels and g-gradients.

The first research aim was to vary gravity loading conditions (g-level and g-gradient) by changing the tilt angle and angular velocity of a short-radius centrifuge, and characterize the physiological responses to this: specifically, heart rate, blood pressure, and calf volume. Further, we examined the effect of light exercise on these basic physiological parameters. Comparing the exercise and no-exercise cases allowed us to draw conclusions as to the usefulness of exercise in reducing responses that could eventually lead to syncope.

We also wished to show that exercise in an artificial gravity environment is beneficial. Ideally, we would have showed that exercise on a centrifuge counteracts the physiological deconditioning that occurs due to weightlessness. However, we were unable to expose subjects to a weightless environment, or to bedrest or another spaceflight analog, using our facilities. Therefore, we took a different approach.

**Hypothesis 2.** An exercise program consisting of stair-stepping on a centrifuge will effectively improve fitness, as measured by aerobic capacity, muscular strength and endurance, and body composition.

The second research aim was to investigate if exercise in an artificial gravity environment produced fitness benefits for healthy subjects. We enrolled subjects in an eight week exercise program using a small stair-stepper and resistive arm bands mounted to the MIT Short-Radius Centrifuge.

Detailed hypotheses will also be presented at the beginning of each Experiment chapter.

### 1.2 Thesis outline

The Introduction provided here presents artificial gravity combined with exercise as a potential countermeasure. Contributions are listed.

**Chapter Two, Background,** reviews previous research on the physiological effects of long-duration spaceflight, current countermeasures, and research into the use of exercise in an artificial gravity environment.
Chapter Three, The effect of light exercise on the physiological response to a gravity gradient, describes the methods and results of Experiment 1. The purpose of this experiment was to characterize the physiological responses to centrifugation with varying parameters (g-level and radius, as simulated by a tilting centrifuge), and to investigate the mitigating effect of light exercise on these physiological responses.

Chapter Four, Effectiveness of stair-stepping during centrifugation, describes the methods and results of Experiment 2. The purpose of this experiment was to quantitatively determine the fitness benefits that could be obtained from an eight-week centrifuge/exercise program, using healthy ambulatory subjects.

Chapter Five, Discussion, describes implications of the results from both Experiments 1 and 2, and relates the results to relevant literature. Future work is suggested.

Chapter Six, Conclusion, summarizes the pertinent results from this research effort. Recommendations are made for this system as a spaceflight countermeasure.

1.3 Contributions

The work presented in this thesis offers two unique contributions to the field of spaceflight countermeasures. In particular, we have explored aspects of exercise in an artificial gravity environment as a feasible and potentially effective countermeasure.

Experiment 1 was the first direct measurement of the influence of varying tilt to simulate varying radii of a centrifuge. This was allowed due to the unique capabilities of the European Space Agency (ESA) centrifuge used for the experiment.

Experiment 2 measured the effectiveness of a fitness program consisting of exercise on the MIT short-radius centrifuge. Specifically, previous studies have begun to explore the effect of exercise on a centrifuge as a countermeasure to physiological deconditioning for bedrested subjects, but the present study examined fitness benefits to healthy subjects using a centrifuge and exercise system. In addition to these measures, Experiment 2 characterized the use of a stair-stepper for use on a centrifuge. Stair-stepping may be more beneficial than cycle ergometry due to the inherent impact loading, as well as the physical/biomechanical motion, which is more similar to walking, as outlined in the Discussion. Finally, Experiment 2 required several major hardware elements to be added to the MIT short-radius centrifuge, including stepper instrumentation (potentiometer mount, and foot force plates designed and built in-house), a
centrifuge frame that allows elements to be mounted above the subject, centrifuge support hardware to accommodate the stresses of exercise, and physiological monitoring equipment for heart rate and blood pressure.
Chapter Two

Background

The last fifty years have allowed for considerable advances in the understanding of physiological responses to weightlessness. Some of these responses are problematic upon return to Earth (or, potentially, any gravity environment). In the first part of this chapter, we will review the knowledge base of these responses, which are usually called “deconditioning” in the context of spaceflight. A number of countermeasures have been developed to prevent this deconditioning from occurring, and these approaches will be reviewed in the second part of the chapter. The third and fourth parts of the chapter, respectively, address the possible countermeasures of artificial gravity, and exercise combined with artificial gravity.

2.1 Spaceflight related physiological deconditioning

Long-duration spaceflight poses significant physiological problems, in large part due to deconditioning of systems that have developed to tolerate Earth’s gravity. For example, bone maintenance and growth require loading [13]; in ambulatory humans, normal daily activity will maintain the bones in the lower body. During spaceflight the lower half of the body is unloaded and largely unused, resulting in significant bone loss (up to ~1.5% bone mineral density loss per month in the hip [1].) Likewise, cardiovascular deconditioning occurs due to the absence of orthostatic stimulus that, on Earth, requires a fast series of autonomic nervous system responses, described below, which serve to return blood to the heart and brain when transitioning from the supine to standing position. Without this stimulus, there are changes in vascular tone [14] as
well as autonomic function [15]. There are also considerable changes in muscle mass and strength due to spaceflight [2], and changes in neurovestibular function [16]. This section reviews the physiological deconditioning that occurs due to spaceflight.

2.1.1 Musculoskeletal system

Bone loss is considered to be one of the most pressing physiological concerns for long-duration spaceflight [14]. Bone mineral density (BMD) is lost at a rate of approximately 1% month in the spine and 1.5% per month in the hip, with losses in both trabecular and cortical bone [1, 17]. These losses, seen for crewmembers on ISS, are in spite of countermeasures intended to prevent this [18] – see Figure 1. Similar losses were seen in crewmembers (BMD losses of 3.4% (p<0.001) after 16-28 week Mir missions (n=14) [2]).

Bone is maintained and increased through mechanical loading ([13], although in the case of clinical osteoporosis, there are other reasons for bone loss). The bone loss that is observed during spaceflight is primarily seen in the lower body, and is most likely due to disuse of the legs. In large part due to disuse, elderly people often experience bone loss, which increases their risk of fracture if they fall. Consequently, this group serves as a useful analog for spaceflight-deconditioned crewmembers, and development of bone-related countermeasures [19]. Normal daily activity results in a large number of low magnitude bone strains and a small number of high magnitude bone strains, as has been measured in animals1. More specifically, lower body activities on Earth require fairly high forces at a somewhat low frequency (e.g. walking provides ~1.4 times body weight [20] but at a frequency of only around 1 Hz). Since elderly people may be unable to experience high magnitude lower body forces (for example, if they seldom exercise), an alternative is to expose them to very low magnitude, but high frequency impacts for a short time every day. This has led to the concept of a “vibrating plate” for bone maintenance [21]. Recent research into the vibrating plate concept has revealed that it is possible to maintain bone mineral density in both animals and in postmenopausal women, through a daily prescription of vibrating plate use [21-23], and is certainly an interesting option for spaceflight. Low magnitude, high frequency stimulus has also been beneficial to BMD in the spine and tibia for children with disabling conditions [24].

1 In this case, microstrains were measured using strain gauges implanted on the animal’s tibia. Strain is a measure of deformation of an elastic material.
Another consequence of disuse is significant losses in muscle size and strength after extended time in microgravity. Lean body mass decreased by 3.5% (p<0.001) after 16-28 week Mir missions (n=14) [2]. Muscle strength changes were seen during the Skylab missions, in both the legs and the arms, although much greater losses were seen in the legs [20].

The above results indicate that the current rates of bone and muscle loss are not acceptable for future long-duration flights. Bone loss must be slowed or stopped in order to reduce fracture risk, so that the astronauts can safely walk (or in a worst case scenario, fall) in a gravity environment. Likewise, strength changes present considerable danger in the context of bone loss: if the astronaut can not support him/herself, the risk of falling increases.

### 2.1.2 Cardiovascular

In general, spaceflight results in an overall decrease of blood pressure and heart rate while in space [18, 27]; see Figure 2. The diurnal variability of heart rate and diastolic pressure
is also reduced during flight [27]. However, these changes are generally without consequence in-flight. The main concern for cardiovascular health is the possibility of orthostatic intolerance upon return to Earth or another gravitation environment; that is, presyncope or syncope resulting from the change to an upright posture from supine in a gravity field. Postflight orthostatic intolerance is experienced by approximately 20% of astronauts [28, 29]. Orthostatic intolerance is markedly worse after long-duration spaceflights (120-190 days, 5 of 6 became presyncopal) than short duration (less than 14 days, 5 of 20 became presyncopal) [29]. Orthostatic intolerance tends to be more of a problem for women than men; in a study of 35 astronauts after 5- to 16-day spaceflights, a significantly higher percentage of women became presyncopal during a tilt-test, and had greater postflight losses in plasma volume [28]. Sawin et al [30] also showed that the effect of body position on heart rate and blood pressure is exaggerated after spaceflights of less than 16 days in duration (Figure 3).

![Graph](image)

**Figure 2.** Heart rate and systolic and diastolic pressures on 2 occasions before flight, 2 occasions in flight, and 1 occasion after flight. Values are means ±SE; n, number of subjects. Note that all values increase significantly postflight from preflight when the crewmembers are awake. From [27].
The two most likely reasons for orthostatic intolerance are decreased peripheral vascular resistance and decreased stroke volume [31]. (It is important to note that to prevent postural hypotension, cardiac output is the relevant variable, not stroke volume. Cardiac output is the product of stroke volume and heart rate, which increases upon standing (Figure 5); if stroke volume decreases proportionally more than heart rate increases, there will be a net decrease in cardiac output.) Decreased peripheral resistance (perhaps an increase in leg vein distensibility) was identified as the major difference in physiological responses between subjects who did and did not finish a postflight 10-minute stand test (9 out of 14 were non-finishers, flights up to 14 days) [3]. Decreased stroke volume may be due in part to cardiac atrophy, but is probably primarily due to reduced preload resulting from an overall decrease in blood volume [31]. This hypovolemia occurs early in the mission and has been observed in spaceflights as early as Skylab [18]. Other mechanisms may certainly exacerbate the problem; it has been hypothesized, for example, that skeletal muscle atrophy may also contribute to postflight postural hypotension [32], and also that changes in vestibular function while in space may affect the responsiveness of the baroreflex [33].

Changes in the response of the autonomic nervous system to 1-g postural adjustments may play a role in the problem of postflight orthostatic intolerance, although we must take into

Figure 3. Stress (a) heart rate and (b) arterial blood pressure response (±SD) to entry, landing, and egress for Shuttle flights of up to 16 days in duration. Both heart rate and arterial blood pressure responses to standing are much higher after flight. Figures from [30].
account the difficulty in distinguishing between changes in control (autonomic nervous system, discussed below) versus downregulation of effector mechanisms (outlined above). The investigations presented here suggest that the autonomic response to standing is reduced in response to microgravity, and this adjusted response may linger postflight. Specifically, the baroreflex response is partially responsible for initiating compensatory cardiovascular mechanisms that maintain cerebral blood flow when standing upright in Earth’s gravity. It is extremely likely that reduced baroreflex sensitivity is partially responsible for orthostatic intolerance after spaceflight [31]. For the discussion that follows, we will distinguish between vagal (generally inhibitory) and sympathetic (generally excitatory) nerve responses; the response of the baroreceptors calls on both of these mechanisms. When standing from a sitting position, the drop in pressure at the carotid baroreceptors initiates both sympathetic and vagal responses to increase heart rate and vasoconstriction and bring the pressure at the level of the baroreceptors back to nominal levels [34].

A study of three Russian cosmonauts after long-duration (9 month) Mir flights indicated that vagal-cardiac nerve activity was reduced after long-duration spaceflight relative to preflight, as was vagal baroreflex gain, and these changes persisted for up to two weeks after spaceflight [35]. Studies during the Neurolab STS-90 mission also supported the notion that vagal nerve traffic decreases with extended weightlessness; however, by observing the blood pressure response to the Valsalva maneuver, it was determined that the sympathetic baroreflex response was not affected [36]. Another Neurolab experiment induced cardiovascular stress using Lower Body Negative Pressure (LBNP), and determined that the sympathetic response (including heart rate, blood pressure, muscle peroneal sympathetic nerve activity, and plasma norepinephrine content) was maintained or slightly elevated during and after flight [37]. In another study, changing external neck pressure (simulating tilt-test induced pressure changes) was used to investigate the vagal-cardiac reflex responses of postflight astronauts; in general, heart rate was higher (R-R interval was shorter) for pressure changes after 4-5 day spaceflights, indicating that the “operational point” (the relative buffering capacity of the baroreflex for pressures above and below the resting level) decreased significantly after spaceflight ([15, 38], see Figure 4), although there has been some dispute over interpretation of the operational point, as Figure 4 may simply show that heart rate after landing was higher at rest, though there is little change in baroreceptor sensitivity (slope).
It is known that the baroreceptor system resets itself after one or two days to the pressure level to which it is currently exposed, such that baroreceptors are not used for long term regulation of mean arterial pressure [39]. This lends credence to the notion that the overall control of the cardiovascular system is likely altered after a period of time in space.

A computational (lumped parameter, closed loop) model of the orthostatic response to standing has been successfully created [40]. By decreasing total blood volume by 300 mL, heart rate gain by 25%, arterial resistance gain by 16%, and venous tone gain by ~5%, the authors were able to successfully reproduce the effect of a stand-test on landing day after a spaceflight; specifically, a slower and elevated heart rate response – see Figure 5. This suggests that spaceflight influences on the cardiovascular system may be successfully quantified, which is useful in developing targeted countermeasures.

Another cardiovascular change seen post-spaceflight is a reduction in aerobic capacity. The average $\dot{V}_{\text{O}_2}$ (oxygen uptake in mL/min, a measure of aerobic capacity) at a constant heart rate (160 beats/min) decreased by 21% on the first day postflight for the Apollo 7-11 crewmembers [41]. This has also been observed for space shuttle crewmembers: after 9 or 14 days in space, a submaximal cycle ergometer test resulted in a significant decrement of $\dot{V}_{\text{O}_2}$-max.

Figure 4. Carotid baroreceptor vagal-cardiac reflex responses before flight and on landing day. Closed symbols, position of operational points. Average operational point was reduced significantly on landing day, but slope and range were not. From [15].
22% below those that were measured preflight [42]. The authors attribute this entirely to decreased stroke volume and cardiac output; peak heart rate, blood pressure, and arterio-venous oxygen difference were unchanged. Interestingly, during inflight testing before landing, this significant $\dot{V}_\text{O}_2$-max decrease was not observed – in fact, the astronauts’ aerobic capacity was similar to that observed two weeks preflight [42].

In summary, cardiovascular changes due to weightlessness, including both control and effector mechanisms, are completely appropriate and do not pose any problems when in space. However, postflight functionality may be impaired due to changes in the cardiovascular system. The biggest direct concern for astronauts is the risk of fainting due to orthostatic intolerance. Combined with elevated fracture risk due to bone loss, this could be catastrophic. It also reduces the astronaut’s ability to do useful work for a period of time after re-entering a gravity environment. Cardiovascular changes during and after spaceflight are summarized in Table 1.

Figure 5. Simulated (dash-dotted line, [40]) and actual heart rate response (solid line) to the upright posture (supine to standing at time=0). Experimental data taken (a) 120 days before spaceflight, and (b) on landing day. Notice how the Heldt model successfully predicts the slower and elevated heart rate response to standing, after spaceflight. Astronaut data provided by Janice Meck, PhD, NASA, Johnson Space Center, Houston, TX. Figures from [40].
Table 1. Summary of cardiovascular changes during and after spaceflight. Largely summarized from [14].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spaceflight effect</th>
<th>Post-spaceflight</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke volume</td>
<td>Increase, then eventually return to preflight sitting levels</td>
<td>Decreased</td>
<td>Due to low blood volume</td>
</tr>
<tr>
<td>Cardiac output</td>
<td>Increase, then eventually return to preflight sitting levels</td>
<td>Decreased</td>
<td>Due to low blood volume</td>
</tr>
<tr>
<td>Blood pressure</td>
<td>Slightly reduced</td>
<td>Lower when standing</td>
<td>Many astronauts can not complete a postflight stand test due to hypotension</td>
</tr>
<tr>
<td>Heart rate</td>
<td>The same or slightly reduced from preflight</td>
<td>Higher when standing</td>
<td></td>
</tr>
<tr>
<td>Total blood volume</td>
<td>Reduced</td>
<td>Decreased</td>
<td>Major contributor to postflight orthostatic intolerance</td>
</tr>
<tr>
<td>Venous tone</td>
<td>Unknown</td>
<td>Decreased</td>
<td>Decreased ability to vasoconstrict may be partially responsible for postflight orthostatic intolerance</td>
</tr>
<tr>
<td>Aerobic capacity</td>
<td>May be maintained or increased with exercise</td>
<td>Decreased</td>
<td></td>
</tr>
</tbody>
</table>

2.1.3 Neurosensory changes

Space motion sickness (SMS) was observed as early as Gemini 7 [18], and has been a persistent problem. It is estimated that 71% of astronauts experience SMS [43]. SMS may be explained by a sensory-motor conflict (that is, internal conflict between sensory systems, such as the visual and vestibular systems) [16]. SMS is particularly a concern for first-time astronauts, but usually disappears in the first three days. Illusory sensations can also affect performance in all phases of flight [16]; many types of illusions have been documented [44]. Some of these illusions are due to the continual freefall environment of orbiting spaceflight. This eliminates the gravity vector and removes its stimulation of the otolith organs, which then perceive only linear accelerations, not the absent (but expected) gravity vector. Further, as other crewmembers move about without a common vertical, the frame of the room no longer matches the astronaut’s idiotropic vector (the vector along the body axis) and the polarity cues (the expectation that other crewmembers should also have their feet pointed towards the floor). Adaptation usually occurs within a few days, but disorientation due to the altered vestibular sensations makes navigation difficult in a space station with many corridors and modules.

Postflight changes have been observed as well, including changes in eye/head coordination, locomotion, posture control, and illusory sensations that occur when making head
movements [45]. After Skylab spaceflights of 28, 59, and 84 days duration, crewmembers were tested for postural equilibrium using a test to maintain balance on a narrow rail with eyes open and closed. After spaceflight, there was a small decrement in performance in the “eyes open” condition and a large decrement in performance in the “eyes closed” condition, indicating a greater reliance on visual cues for postural maintenance. The crewmembers regained preflight postural stability after approximately two weeks [46].

There may also be a relationship between vestibular stimulation and the baroreflex response; in a controlled experiment, subjects undergoing yaw rotation exhibited reduced carotid baroreflex responses compared with no-rotation controls [33]. Changes in the gain of the vestibular system has been suggested as one reason for the orthostatic intolerance seen postflight, as the otoliths may play a part in regulating blood pressure during changes in posture in 1-g [47].

The neurosensory effects of weightlessness are problematic in that they include illusions and motion sickness. Reduced balance would lead to an increased risk of falling upon return to a gravity environment. In the case of landing on another planet, this may also reduce the astronaut’s mobility for EVA’s scheduled early in the mission. Although balance is clearly an operationally relevant concern, it will not be addressed in detail in this thesis; rather we will focus on exercise effects of artificial gravity. However, otolith stimulation due to artificial gravity could prove to be helpful with respect to vestibular changes.

2.2 Current countermeasures

In the fifty years of active spaceflight programs, many countermeasures have been developed to address the musculoskeletal, cardiovascular, and neurovestibular changes. In this section we will discuss current countermeasures to physiological deconditioning. In many studies described in this section, a spaceflight analog was used to initiate physiological deconditioning; in most cases, this analog was 6° head-down bedrest. Head-down bedrest has been shown to reproduce the effects of weightlessness in terms of cardiovascular changes [48], although the fluid shift may not be as great in magnitude or effect [14]. Head-down bedrest has also been shown to reproduce muscular atrophy [49, 50] and skeletal effects [51-53] of weightlessness, and is used widely for its availability.
2.2.1 Exercise

Exercise during bedrest or spaceflight has generally been effective in maintaining or increasing postflight exercise responses (e.g. aerobic fitness [4]). For example, intensive intermittent exercise training (at 40% $\dot{V}_{O_2}$-max and greater) performed during two 30-min periods daily for 5 days per week during 30-day bedrest maintained plasma volume and $\dot{V}_{O_2}$-max at baseline levels, as opposed to 16-18% losses in control (no-exercise) bedrest subjects [54]. Also, aerobic training three times per week (>20 min per session) at heart rate levels greater than 70% age-predicted HR$_{max}$ resulted in minimal aerobic decrements postflight in up to 16 day missions [30].

Current exercise countermeasures on ISS include resistive, treadmill, and cycle ergometry exercise. The resistive exercise device allows astronauts to target specific muscle groups at weights of up to 136 kg (300 lbs). The treadmill requires subjects to wear a shoulder and hip harness, and allows the option of motorized (up to 16 km/hr) or unmotorized belt movement (unmotorized belt movement provides additional resistive loads since the astronaut must move the belt manually). The cycle ergometer is used in the recumbant position, and resistance against pedaling can be varied manually or electronically. (Information from exploration.grc.nasa.gov, accessed 11 April 2008.)

In the sections below, we will review the ways in which exercise is or is not effective in combating the physiological deconditioning of the systems described in Section 2.1.

2.2.1.1 Cardiovascular

Most studies examining the effectiveness of exercise as a countermeasure to orthostatic intolerance do not strongly support its use. A direct comparison of six exercisers (subjects who underwent a progressive five day per week running program) vs. controls indicated that there was no difference in the two groups in terms of g-tolerance, as measured by responses to slow- and rapid-onset centrifugation, although the exercisers experienced increased aerobic endurance as measured by $\dot{V}_{O_2}$-max [55]. Heart rate variability (an indicator of autonomic control) also does not vary significantly between athletes and non-athletes at rest and during head up tilt [56]. Five months of high intensity exercise training in sedentary, healthy adults did not change heart rate variability (measured over 24 hours of Holter monitoring) or baroreflex sensitivity (indicated
by the heart rate response after an injection of phenylephrine) [57]. Six months of endurance training three times per week for 30-45 minutes per session did not affect heart rate and blood pressure responses to a tilt-test in healthy elderly subjects [58]. For subjects who underwent 30 days of bedrest, there was no significant difference in tilt table tolerances between isotonic and isokinetic exercise groups and controls [59].

It has been suggested that the effect of training on autonomic cardiovascular regulation is bell-shaped (Figure 6): a moderate amount of training will improve autonomic control, whereas continued training could reset it to the untrained state [60]. The left side of this bell-shaped effect may be explained because moderate amounts of training will increase a subject’s plasma volume [61] and may be particularly useful for subjects with a low initial tolerance [62]. On the other side, though, there is some evidence indicating that highly fit individuals have lower orthostatic tolerance than less fit individuals [61, 63]; Ogoh et al [64] attribute this to reduced carotid baroreflex responsiveness (in this case, during head-up tilt).

![Figure 6. Notional curve showing that the least fit and the most fit individuals may have the lowest orthostatic tolerance (see text for details).](image)

There is some evidence that exercise could be beneficial for certain cardiovascular mechanisms. Exercise may be effective in mitigating the bed-rest induced increases in leg vein distensibility. This was determined experimentally with subjects exposed to LBNP after 60 days of bedrest [65]. The mechanisms that lie behind this overall mitigation may be that during supine exercise there is an increase in venous tone (venoconstriction), even in the non-exercising limbs, in order to increase ventricular filling [66].

It has been suggested that a single bout of high intensity exercise may increase baroreflex sensitivity before landing [67]. Subjects in bedrest exercised with their legs (dynamic knee
extension exercise and isometric exercise using the same device) on day 8 of bedrest, and their vagally-mediated cardiac response to neck pressure was measured 24 hours after the exercise session (specifically, R-R interval vs. carotid pressure). Before the exercise (on day 7), the gain of the response was significantly decreased relative to pre-bedrest values; however, on day 9, the gain had significantly increased from both its day 7 value and its pre-bedrest value [67]. This suggestion for maximal exercise before landing has been disputed, however. On the last day of spaceflights of 8-14 days duration, four crewmembers performed a single bout of maximal exercise 24 hours before landing, while four crewmembers served as controls. 1-2 hours after landing, they completed a 10 minute stand test; there were no differences in blood pressure or heart rate responses between the two groups [68]. Thus, this suggestion of a single bout of high intensity exercise has neither been demonstrated nor disproved as a potential countermeasure.

While exercise in space tends to maintain exercise responses when the astronauts return to Earth, it is evident from the above studies that there is limited evidence of its usefulness against orthostatic intolerance. This may be due in part to the fact that exercise in space or during bedrest requires external loading (bungees), which do not provide an orthostatic challenge. Exercise on a centrifuge, reviewed below, provides an orthostatic challenge and may be a better stimulus for maintaining cardiovascular function.

### 2.2.1.2 Bone

Exercise that involves impact loading seems to be most useful for maintaining or increasing bone [69-74]. High impact loading has been observed to significantly increase BMD in female gymnasts [69]. In this longitudinal 8 and 12 month study of collegiate athletes, both lumbar and femoral neck BMD increased significantly more in gymnasts than in runners, swimmers, or sedentary controls (with the exception of femoral neck BMD in gymnasts versus sedentary controls after 8 months, which only approached significance at p=0.06). The authors conclude that high impact loading induces bone growth in young women. In another study of young female tennis players, authors found that the bone mineral content (BMC, an absolute measure of bone mass) of the humeri of pre-pubescent girls was 11-14% higher in their playing arms than their non-playing arms; this was a result of an increase in cortical area [70]. Likewise, for premenopausal women (n=14) participating in daily high impact exercise, femoral trochanteric BMD increased significantly (3.4%) relative to controls who participated in low
impact exercise [71]. In pre-pubescent children (n=89), jumping off of a 61 cm platform 100 times per day (three days per week for seven months) significantly increased femoral neck and lumbar spine BMC over controls who did stretching exercise [72]. Another study on postmenopausal women revealed that a 24-week (3 sessions per week) exercise program involving treadmill walking and bench-stepping significantly increased lumbar BMD (L2-L4, 2.0%) and femoral neck BMD (6.8%, n=22), whereas those who women did not exercise (n=21) experienced significant losses in both [73].

Weight training is also useful for bone maintenance and growth. In early postmenopausal women, a 9-month weight training regimen significantly increased lumbar bone mineral density over control subjects (no weight training, n=24) [75]. In a 17-week bedrest study, subjects who exercised 6 days per week using a resistive exercise device had no significant changes in regional BMD values, except for the lumbar spine, which increased significantly from pre-bedrest [52]; for controls, all regional BMD values decreased, many of them significantly. In general, weight training is a better stimulus for bone growth than many endurance activities that are aimed to improved aerobic capacity [76].

Four subjects tested during spaceflight (ISS) showed that the foot forces during running on the treadmill using resistive bungees for external loading were only approximately 1.3 times body weight [77]. Comparatively, jogging on Earth produces foot forces approaching three times body weight (Figure 7) [20]. The four subjects tested on ISS experienced BMD losses in the femoral neck, hip, and lumbar spine, presumably due to the relatively low impact loading. Despite current countermeasures, bone losses on ISS have generally been 1-2% per month [18]. Increasing foot forces during running or other exercise may help with bone maintenance.

The above studies support the use of a space exercise program that includes impact loading, but the current space exercise program is not sufficient for bone maintenance. It should be noted that most of the above studies regarding impact loading reference young athletes or post-menopausal women, because these populations gain or lose bone at higher rates than many other groups. However, neither of these groups is an accurate model for the astronaut population, and as such should not be used directly as models for astronaut bone losses or gains. What these studies do indicate is that, in terms of bone maintenance during spaceflight, we should strongly consider dynamic impact loading.
2.2.1.3 Muscle

In general, weightlifting (or resistance training) alone is not sufficient to improve or even maintain aerobic capacity (as measured by $\dot{V}_{O_2}$-max); however, in a three-year longitudinal study of male subjects, weight training did increase both lean body mass and maximal muscle strength in various tests [78]. Resistance training may be an effective countermeasure to reductions in muscle volume and strength. In the 17-week bedrest study mentioned in the section above, subjects who exercised 6 days per week using a resistive exercise device showed increased strength, while controls had slightly decreased strength as measured by several regional strength tests [52] (Figure 8). In a 30-day bedrest study, subjects were divided into isokinetic and isotonic knee extension groups; in a post-bedrest test, the isotonic group maintained and the isokinetic group increased total work ability [79]. However, in a shorter bedrest study (14 days), subjects who performed five sets of resistance squats to exhaustion did not exhibit any attenuation to strength losses as measured by isokinetic knee extensions (torque vs. velocity and torque vs. position, specifically) [80]. This may be related to the principle of training specificity; that is, testing in the same manner as the subject trained – see Chapter Four.
Figure 8. Change in strength (isotonic, 1-repetition maximum) after 17 weeks of bedrest for controls (open bars) and subjects who did not exercise and who exercised on a horizontal exercise machine. Exercise increases strength for subjects in bedrest. Figure from [52].

During Skylab 4, a primitive treadmill (Teflon surface) with resistive bungees that provided approximately 80 kg of loading allowed crewmembers (n=3) to perform 10 minutes per day (3 month mission) of walking, jumping, or jogging, and as a result, these crewmembers saw increases in leg extensor strength of 2.4% postflight [81]. This is in contrast to the previous two Skylab missions, in which crewmembers exercised using only a cycle ergometer and primitive resistive device, and saw muscle strength and volume losses. Based on these results, Thornton [81] advocates treadmill exercise as a necessary countermeasure to maintain locomotion abilities and leg strength. More recently, treadmill data (using a treadmill similar to that on ISS) has been obtained using either parabolic flight or a horizontal configuration to simulate microgravity. Researchers have identified the importance of the external loading in achieving useful foot forces; a major limiting factor of the harness is the comfort the crewmember [82, 83].

It is evident that externally-loaded exercise is probably sufficient for muscle maintenance, particularly an exercise program that includes resistance training. For this reason, muscle maintenance may be the most straightforward aim of a space exercise program.
2.2.1.4 Other exercise considerations

Exercise training may prevent falls in the elderly [84]. Specifically, healthy elderly people who were randomly selected to participate in a moderate exercise program in a group setting performed significantly better than well-matched controls in three of six balance tests (after 12 months of exercise intervention [85]). These subjects also had a 40% lower rate of falls than the control group over the year-long intervention period.

As a sidenote, within the astronaut population, there have been a large number of orthopedic injuries both pre- and post-flight, in part due to the very athletic nature of this group [86]. This brings to attention the importance of careful training protocols when considering exercise countermeasures for astronauts.

In summary, exercise is the most readily used and available countermeasure, but has not been shown to be sufficiently effective in preventing many of the physiological problems postflight, in particular orthostatic tolerance and bone maintenance.

2.2.2 Pharmaceuticals

There has been limited success with pharmaceuticals as spaceflight countermeasures. Bisphosphonates can be given for bone loss, and antioxidants have been suggested as a countermeasure to radiation exposure and may also inhibit muscle atrophy [14]. Many other potential drugs have also been suggested for bone loss, but most have significant side effects or the long-term effect is not known [14]. Amino acid supplements are promising for the purpose of stimulating muscle protein synthesis, as has been shown in bedrest studies [50].

Pharmaceuticals that have been used to treat space motion sickness include scopolamine, promethazine, dimenhydrinate and diphenhydramine, meclizine, chlorpheniramine, amphetamine and dextroamphetamine, and ephedrine [14]. Concerns that promethazine may affect autonomic cardiovascular control mechanisms were not found in an Earth-based study of healthy subjects [87]. A possible countermeasure to orthostatic intolerance could be erythropoietin, which raises hematocrit: this could aid in increasing blood volume, although it could also raise the hematocrit itself to unsafe levels by increasing the viscosity of the blood [14]. Midodrine, a vasoconstrictor, has been shown to prevent orthostatic intolerance (hypotension and presyncope) in subjects undergoing a tilt-test after 16 days of bedrest [88]; however, its use
alongside promethazine has been shown to result in somewhat severe akathisia (anxiety or restlessness [89]).

Pharmaceuticals, then, are quite useful in treating motion sickness and have great potential to mitigate bone loss and possibly orthostatic tolerance, but side effects and contraindications must be carefully characterized and monitored.

### 2.2.3 Lower Body Negative Pressure

In normal standing, the hydrostatic blood pressure increase in the legs results in a larger pressure differential between the inside and outside of the legs than when lying supine. The motivation for lower body negative pressure (LBNP) is also to increase this differential, by reducing the pressure outside the legs to something lower than atmospheric pressure. Generally LBNP consists of a closed chamber around the lower half of the body in which the pressure can be reduced. In a 30-day bedrest study involving paired identical twins, supine subjects underwent daily LBNP in a large chamber in which they were also able to exercise on a vertical treadmill [90]. These subjects exhibited less of an increase in markers of bone resorption than controls. The authors hypothesize that the increase in blood flow to the lower extremities due to the LBNP, and the resulting increased perfusion of the bones of the lower limbs, may stimulate the maintenance of bone integrity (blood flow was not measured explicitly in this experiment). Reduction in skeletal perfusion has been linked to losses in bone mass in rats [91]. It could be useful as a countermeasure to orthostatic intolerance as well. LBNP has primarily been used as a countermeasure in Russian spaceflights with some success, and was also tested on Skylab [92, 93]. The Skylab studies provided evidence that a four hour treatment session of LBNP may be effective for approximately 24 hours in preventing orthostatic intolerance (measured in space by a second session of LBNP decompression the day after the treatment). However, NASA deemed the system too cumbersome to use in practice. Specifically, continuous health monitoring from Earth was not possible due to periodic loss of communications, and it was not practical to require astronauts to undergo several hours of LBNP 24 hours before landing, particularly in the case that the landing was delayed (John Charles, personal communication 10 April 2008).
2.3 Artificial gravity

Artificial gravity, which has never been implemented as a spaceflight countermeasure, has been studied and documented extensively in Earth-based studies [8, 12]. Many recent investigations have characterized and quantified the illusory sensations and motion sickness that result from making head turns on a centrifuge, and have found that it is possible to adapt to this through various strategies [94-100].

Qualitatively, artificial gravity produces the same cardiovascular response as head-up tilt (with the notable exception of the longitudinal g-gradient produced by artificial gravity, see Chapter Three); therefore, it is reasonable to hypothesize that artificial gravity will be an effective countermeasure against spaceflight induced cardiovascular deconditioning, just as standing prevents orthostatic intolerance during bedrest (e.g. [53], see Section 2.4 below). Specifically, observed decreases in stroke volume, increases in heart rate, and a resulting slight decrease in cardiac output, seen with higher g-levels, are similar to the orthostatic response [101]. Likewise, 30 RPM short-radius centrifugation has been shown to produce heart rate responses in supine subjects similar to 1-g in upright subjects [102]. Preliminary results from a very recent NASA bed rest study support the use of artificial gravity as a countermeasure to orthostatic intolerance [103].

It has been shown directly that centrifugation may reduce the changes in autonomic control of the cardiovascular system that occur due to bedrest. In a short, 4-day bedrest period, subjects who underwent twice-daily 30-min 2-Gz centrifugation did not experience significant changes in cardiovascular control, whereas those who were in bedrest alone did experience such changes, as determined by spectral analysis of resting heart rate [9]. One hour per day of 2-Gz centrifugation also attenuated the loss of plasma volume otherwise seen during four days of bedrest in 10 male subjects [104]. There is limited evidence that artificial gravity during spaceflight may help maintain orthostatic tolerance upon return to Earth; during a 16-day mission, four crewmembers were exposed to 1-g centripetal acceleration (measured at the center of the head – for this particular centrifuge, the center of rotation was through the torso). Upon return to Earth, these astronauts did not experience orthostatic intolerance. If in fact the centrifugation was responsible for the astronauts’ orthostatic tolerance, the authors suggest that the mechanism may be preservation of the gain of the otolith-sympathetic reflex [105].
With the exception of the study above, centrifugation has not been used in space. It is immensely promising as a countermeasure, as it produces nearly the same effect as Earth’s gravity (see discussion of g-gradient, Chapter Three.) In the final section of this chapter, we will outline one potential use of artificial gravity: a natural force background for exercise.

2.4 Artificial gravity and exercise

The feasibility of a bicycle ergometer on a centrifuge has been shown previously [106-112]. Other types of exercise that have been successfully tested on a centrifuge are treadmill running [113], squats against body resistance or extra resistance [114, 115], and stair-stepping [116].

One concern is that crewmembers will not be able to tolerate centrifugation after being in space for some time, as they will already have become somewhat deconditioned. The cardiovascular response to centrifugation is similar to head-up tilt, and may result in the same presyncopal symptoms. Decreased g-tolerance on a centrifuge, due to bedrest, has been shown experimentally [117].

It is possible that exercise could prevent orthostatic intolerance during centrifugation, illustrated in the following study. Using a short-radius centrifuge outfitted with a cycle ergometer, investigators tested the g-tolerance of subjects with and without the use of the cycle ergometer during centrifugation [108]. They defined a “g-score”, which was the product of the g-level at the heart (vector directed towards the feet) and the time until presyncope occurred. The test consisted of sequentially increasing g-levels. The authors found that when subjects used the cycle ergometer during the test, they were able to achieve significantly higher g-scores, hypothesized to be due to the repetitive muscular contractions in the legs, which act as a pump to aid in venous return. To understand this effect, we may look at some studies that did not involve a centrifuge. Pollock and Wood [118] measured the pressure in the saphenous vein of the ankle during standing and walking; it is evident that walking decreases the average pressure in the vein (see Figure 9). The velocity of blood flow also increases during repetitive exercise, particularly during the relaxation phase, when the muscles are between contractions [119].

The beneficial effects of lower extremity loading both with and without exercise were shown during a 4-day bedrest study in which subjects either stood or walked for two or four hours per day. Standing was particularly beneficial in preventing orthostatic intolerance,
whereas walking attenuated the bedrest-induced increase in urinary calcium excretion and decrease in maximal oxygen uptake; both standing and walking attenuated the loss of plasma volume [53].

Figure 9. Average changes in venous pressure at the ankle produced by walking 1.7 mi/hr (10 subjects). The shaded part represents increases and decreases in pressure due to the actual muscular contractions. Mean pressure is decreased when the subject is walking, and increases when the subject stops walking. Figure from [118].

The effectiveness of exercise during centrifugation is just beginning to be studied. In one experiment, investigators enrolled twelve male subjects in 14 days of bedrest [10]. Half of the subjects cycled at 40-60 W during 1.2-g centrifugation, periodically during this bedrest period. The countermeasure was effective in preventing an increase in heart rate and an exaggerated response to head-up tilt, seen in the control group, demonstrating the potential effectiveness of exercise in artificial gravity to bedrest-induced orthostatic intolerance induced by head-up tilt. Another study demonstrated the effectiveness in maintaining upright exercise responses: during 20 days of bedrest, countermeasure subjects underwent two sessions of cycle ergometry every other day during centrifugation up to 1.4-g at the heart. This intervention resulted in complete statistical elimination of the significant changes seen in the no-countermeasure group, which included increased minute expired ventilation, increased heart rate, increased respiratory exchange ratio, and decreased stroke volume during submaximal upright exercise ([109], Figure
Among subjects participating in a 20-day bedrest study, those who trained using cycle ergometry on alternate days maintained muscle volume, but not muscle strength [49]. A test of treadmill exercise was performed during 14 days of simulated weightlessness (8 hours of water immersion, followed by bedrest). Subjects were exposed to treadmill exercise either on an inclined plane or on a centrifuge, both of which produced 0.5-g. For both groups, the decreased exercise capacity normally seen in bedrest was mitigated, although neither countermeasure aided in orthostatic tolerance [113].

Antonutto et al [5] suggested a system of two counter-rotating bicycles around the rim of a cylindrical space module, which would eliminate the need for external power but allow the crewmember to experience both artificial gravity and exercise. Constrained cycle ergometers that enable a human-powered centrifuge have been successfully built and used [112, 120, 121].
2.5 Summary

In this chapter we have attempted to portray the urgency of spaceflight physiological deconditioning, particularly in the context of a flight to another planet. Table 2 summarizes some of the major points discussed in this chapter. In the following chapters, we focus on exercise in artificial gravity as a possible solution to some of the deconditioning described in this chapter.

Table 2. Summary of physiological deconditioning and current spaceflight countermeasures.

<table>
<thead>
<tr>
<th>Physiological system</th>
<th>Current spaceflight countermeasure</th>
<th>Effective?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Musculoskeletal: losses in muscle mass and strength, significant decreases in bone mineral density</td>
<td>Resistive and aerobic exercise, pharmaceuticals for bone</td>
<td>Resistive exercise maintains muscle fairly well; nothing has effectively mitigated bone loss.</td>
</tr>
<tr>
<td>Cardiovascular: orthostatic intolerance upon return to Earth.</td>
<td>Aerobic exercise, LBNP (Russian), pharmaceuticals</td>
<td>While aerobic exercise maintains aerobic capacity, it does not maintain orthostatic tolerance. Pharmaceuticals may be more effective, but may interact with each other. Artificial gravity is promising.</td>
</tr>
<tr>
<td>Neurosensory: motion sickness and illusory sensations in space, decrease in balance upon return to Earth.</td>
<td>Pharmaceuticals</td>
<td>Effective in treating motion sickness.</td>
</tr>
</tbody>
</table>
Chapter Three

Experiment 1: The effect of light exercise on the physiological response to a gravity gradient

Initial design questions about artificial gravity will require a decision about the radius of the centrifuge to be used. If a large-radius, continually rotating centrifuge is required, then the design of the entire spacecraft will be dictated by this centrifuge. If, however, short-radius, intermittent centrifugation may be used, then the design of the spacecraft is affected to a lesser extent.

We wish to characterize the physiological responses to short- and large-radius centrifugation. On Earth, this may be simulated by a tilting gondola centrifuge. The addition of Earth’s gravity and artificial gravity produce a g-gradient because the artificial gravity component is dependent on the distance from the center of rotation (Section 3.1 and Figure 11). Additionally, we will investigate the effect of light exercise on these physiological responses.
3.1 Introduction

Artificial gravity acceleration ($AG$) increases with the radius ($r$) and the square of the rotation rate ($\omega$). If a very large-radius centrifuge were used (radius on the order of 1 km), the spacecraft itself would either have to be constructed as a torus, or tethered to an equal-moment object, in order to spin in space. This type of centrifuge would spin continuously, and occupants would walk along the rim of the rotation radius. Conversely, if a short-radius centrifuge were used, the centrifuge could be contained within a non-spinning spacecraft, and astronauts would use the centrifuge intermittently for gravity “doses.” In this case, the length of the subject, aligned perpendicularly to the axis of rotation, is a significant percentage of the centrifuge’s total radius. Since the magnitude of artificial gravity is dependent on the distance from the center of rotation, the component of artificial gravity acting on the head of a subject will be less than that acting on the feet, which are further from the center of rotation.

The effects of the g-gradients\(^2\) induced by such short-radius centrifugation are still unknown. This was the motivation for the use of the Short Arm Human Centrifuge (SAHC, previously located at the University of Antwerp, Belgium) in the present study. The g-gradient presents a unique physiological problem. When standing on Earth, arterial blood pressure in the lower legs is much greater (approximately 180 mmHg) than when supine (approximately 100 mmHg, see [34]) due to the hydrostatic pressure gradient. The volume of blood in the legs is also greater than that in the upper part of the body – approximately 600 mL of blood is displaced from the central circulation to veins in the legs in the two minutes following head-up tilt [34].

\(^2\) G-gradient = (G_{z, feet} - G_{z, head})/G_{z, feet}
Normally, when a subject stands up from a supine position, the primarily sympathetic response initiates compensatory mechanisms (increased vasoconstriction and increased in heart rate) to correct for the rapid fluid shift into the legs and bring arterial blood pressure at the level of the baroreceptors back to nominal levels. On a short-radius centrifuge, we may, for example, choose 1-g at the heart level with the head displaced 0.5 m from the center of rotation (0.6-g); then the g-level at the feet will be 2.4- to 2.5-g, depending on the subject’s height. In this situation, the autonomic response to the blood volume shift to the legs is expected to be more exaggerated than if the whole body were in a uniform 1-g environment, even though the g-level at the location of the baroreceptors will be 1-g or less. This is because the pressure at the level of the legs will be much greater – rather than a hydrostatic pressure gradient in a uniform gravity field, we now have a non-uniform gravity field that increases with distance from the head.

On Earth, a simple way to mimic the g-gradient properties of positioning the subject at different radii on a centrifuge is to tilt the bed (head over feet) on a short fixed-radius centrifuge, where the subject’s head is near-center. If we concern ourselves only with the g-gradient along the head-to-feet axis of the body, then depending on the tilt of the body, varying components of Earth’s gravity and artificial gravity act upon that axis. For instance, if the body is pitched to an angle of $\theta$ degrees with respect to Earth horizontal, and spun about an axis through the head and perpendicular to the floor (as in Figure 11), then the component of Earth’s gravity ($g$) that is acting along the body’s axis is $g \sin(\theta)$. Parallel to this, the component of artificial gravity ($AG$, where $AG = r \omega^2$) that is acting along the body’s axis is $AG \cos(\theta)$. The total linear acceleration ($G_Z$) acting at a given point along the body’s axis at a radius of $r$ from the center of rotation is then:

$$G_Z = g \sin(\theta) + AG \cos(\theta)$$

Equation 2

On a short-radius centrifuge, the g-gradient due to artificial gravity is quite high; that is, the artificial gravity component acting at the head is much less than that acting at the feet (in the case above, it is 1.8- to 1.9-g less). However, the gradient from Earth’s gravity ($g$) is negligible compared to that of $AG$. Therefore, the total gravity acting along the body’s axis (Equation 2)

---

3 See discussion of the baroreceptor response to the pressure difference between the heart and the carotid sinus, below, and also Equation 3.
varies with body length due to the varying \( AG \) component. That also implies that if \( AG \) is a greater contributing factor to the total linear acceleration acting on the body than \( g \), the g-gradient is greater. \( AG \) is a greater contributing factor as \( \theta \) decreases; thus g-gradient increases as \( \theta \) decreases. See Figure 12. Hereafter, \( G_Z \) will refer to this vector sum of Earth’s gravity and artificial gravity, acting along the longitudinal axis of the body.

Figure 12. (a) High gradient spin condition. When spun at a level of 1-g at the heart (additive effect of Earth’s gravity and artificial gravity), the subject will experience 2.5-g at the feet. (b) Low gradient spin condition. When spun at a level of 1-g at the heart, the subject will only experience 1.2-g at the feet.

Equation 2 also implies that hydrostatic pressure will vary with tilt angle. If we define \( d_1 \) and \( d_2 \) to be points along the body (e.g. feet and head), then, for an upright person, the pressure difference from point \( d_1 \) to \( d_2 \) is \( \Delta P_g = \rho g (d_2 - d_1) \), where \( \rho \) is the density of blood \((1060 \text{ kg/m}^3)\) and \( g \) is Earth’s gravity \((9.81 \text{ m/s}^2)\). However, in an artificial gravity environment, the pressure gradient is affected by a non-uniform gravito-inertial field, as mentioned above. Here, \( g = r \omega^2 \) and the distances \( d_1 \) and \( d_2 \) are distances from the center of rotation (and will be substituted into the equation for \( r \)). Therefore, the pressure equation becomes \( \Delta P_{AG} = \rho \omega^2 \int_{d_1}^{d_2} r dr \), or \( \Delta P_{AG} = \frac{1}{2} \rho \omega^2 \left( d_2^2 - d_1^2 \right) \). As with gravity, the equation for total hydrostatic pressure when taking into account both Earth’s gravity and artificial gravity becomes:

\[
\Delta P_{total} = \rho g (d_2 - d_1) \sin(\theta) + \frac{1}{2} \rho \omega^2 \left( d_2^2 - d_1^2 \right) \cos(\theta)
\]

Equation 3

where \( \Delta P_{total} \) is the change in pressure from \( d_2 \) to \( d_1 \) and \( \theta \) is the tilt angle.
Equation 3 is important in the context of arterial blood pressure measurement. The baroreceptor system, which regulates arterial blood pressure, is particularly responsive to the difference in pressure between the heart and carotid baroreceptors (neck). For a given g-level at the heart, at higher tilt angles, there will be a greater pressure drop between the carotid sinus and the heart. This is due to the fact that as the subject is tilted up, his neck moves away from the center of rotation, and the net g-level is greater. So, while a higher g-gradient (lower tilt angle) will result in a greater pressure drop from the head to the feet, the heart/neck pressure drop is actually greater for higher tilt angles.

The autonomic “stress” response to acceleration, particularly hypergravity exposure of greater than 1-g at the feet (as described above), may be necessary for maintenance of the cardiovascular control mechanisms during a long-duration spaceflight. However, there are legitimate concerns that exposure to a gravity environment after some time in space may be too great a stimulus for the deconditioned astronauts. As described in Chapter Two, astronauts often experience orthostatic intolerance and syncope when standing in Earth’s gravity after spaceflight. The same might occur, then, if an astronaut who has been in space for some time is exposed to artificial gravity. In his deconditioned state, the astronaut may experience orthostatic intolerance during centrifugation. However, lower body exercise could help subjects (or astronauts) to tolerate higher g-levels, due to muscular pumping assisting in venous return. The tilting centrifuge allows for a unique platform to explore the mitigating effect of light exercise on a simulated varying-radius centrifuge.

This study examines the heart rate, blood pressure, and lower leg volume responses to various g-gradients in a population of healthy subjects.

For the rest of the text in this chapter, unless otherwise stated, “g-level” refers to $G_z$ (Equation 2), measured at the level of the heart.

### 3.1.1 Hypotheses

**Hypothesis 1.A.** Heart rate and blood pressure will both increase as a result of increasing g-level. Heart rate will increase and blood pressure will decrease with decreasing tilt angles.

We aim to test the effect of g-level and g-gradient on heart rate and blood pressure. As g-level increases, there will be a drop in pressure at the level of the carotid baroreceptors, and
redistribution of blood to the lower part of the body, decreasing cardiac output. To compensate, heart rate will increase and vessels will constrict. Pressure at the level of the carotid baroreceptors will be brought back to nominal levels, and the pressure at heart level (which is measured) will be increased, according to Equation 3. Thus, we expect an increase in both heart rate and blood pressure with increasing g-level. Higher g-gradients from the head to the feet will result in higher volume in the legs and a decrease in cardiac output; to compensate, heart rate should be greater for lower tilt angles. However, the hydrostatic pressure between the heart and the carotid baroreceptors will actually be less for low tilt angles, since the head is closer to the center of rotation at low tilt angles. Thus, the required compensatory response will be less, and blood pressure measured at the heart should be less for lower tilt angles.

**Hypothesis 1.B. Calf volume will increase with increasing g-levels and decreasing tilt angles. Right calf volume will be lower when standing on both feet than when allowing the right leg to relax and hang freely. Calf volume will be lowest, on average, when stepping in place.**

We aim to measure the effects of increasing g-level and increasing g-gradient on calf volume when standing evenly on both feet and when letting the right foot hang with no muscular activation. Since there is a mechanical reduction in venous volume when standing due to small muscle contractions [34], we expect calf volume to be lower when standing than when relaxed, and even lower when stepping in place.

**Hypothesis 1.C. Stepping in place will reduce the heart rate and blood pressure responses to changing g-level and g-gradient.**

We aim to test the effect of very light exercise (stepping in place) on heart rate and blood pressure responses to tilt. The primary reason for increased heart rate and blood pressure during high g-levels is that, with a greater pressure in the legs and a resulting orthostatic challenge, greater compensation is needed in terms of increased cardiac output and vasoconstriction, to aid in venous return and return blood pressure to nominal levels at the baroreceptors. Stepping, however, may act as a mechanical pump to aid in venous return, and reduce the blood pooling in the legs and the resulting orthostatic challenge.
3.2 Methods

This section describes experimental methods to test the above hypotheses, including the required hardware, experimental protocol, and analysis tools.

3.2.1 Hardware

3.2.1.1 Antwerp centrifuge

The Short Arm Human Centrifuge (SAHC) was designed and built by Verhaert Space (Kruibeke, Belgium) for the European Space Agency. At the time of the experiment, the SAHC was in its validation stage at the University of Antwerp, Belgium. The system included two beds on arms opposite one another about the centrifuge axis of rotation, and two chairs offset 90° from the beds (not used for this experiment). The beds had the capability of tilting about a point behind the subject’s back, such that the subject’s head was above his feet. The range of tilt, measured from the horizontal, was -6° (head down) to 45° degrees. The distance from the pivot point to the subject’s ears (measured along the subject’s body) was fixed at 0.85 m, and the distance from the pivot point to the center of rotation (measured perpendicular to the axis of rotation) was 1.36 m (Figure 13). For this experiment, one subject at a time was spun on the bed, lying on her back, with her head towards the center of rotation and feet away from the center of rotation.
3.2.1.2 Foot force plates

The centrifuge foot plate was equipped with two force plates, one beneath each foot. The force plates were designed at MIT, each using four strain gauge components from commercial digital scales. Voltage output from the four strain gauges was added to give one continuous force value per foot. See Appendix A for full documentation.

3.2.1.3 Instrumentation

Each subject was instrumented with a Portapres® continuous blood pressure monitoring system (model 2.0 unit, Finapres Medical Systems, Amsterdam, The Netherlands). The Portapres® was set to the “height correction” setting, which corrected the finger arterial pressure to arterial pressure at the heart level (taking into account the effects of both Earth’s gravity and artificial gravity, as described by Equation 3). According to the Portapres® 2.0 User’s Manual:
“Portapres comes with a height correction system to compensate hydrostatic level effects due to movement of the measured finger(s) with respect to the reference point at heart level. The height correction system consists of a liquid filled tube connected at one end to a pressure transducer. The other end is closed with a very compliant plastic bag contained in a small cylindrical housing. The tube material and liquid are matched with respect to the coefficient of linear thermal expansion. Therefore, pressure changes within the tube due to temperature changes and/or bending of the tube are less than 0.1 mmHg/°C. During a measurement the transducer is placed at the measured finger and the compliant ending at the reference (usually heart) level by means of Velcro. Thus, height changes of the measured finger(s) are continuously sensed. . . . . . The height signal is lowpass filtered and subtracted from finger pressure. Thus, slow changes in blood pressure due to hydrostatic effects are compensated.”

The subject was also instrumented with a Philips® ECG and SpO₂ finger sensor (model M1191AL) and blood pressure cuff (model M1574A), all of which were used only for safety monitoring during the experiment. Additionally, each subject was fitted with four iridium circumferential strain gauges (Hokanson®; Bellevue, WA): one placed at approximately the thickest part of the gastrocnemius and the other placed approximately at the base of the soleus. Measuring circumference of the lower leg is an appropriate way to estimate volume changes [122].

3.2.2 Experimental protocol

Sixteen complete data sets (3 females/13 males) were obtained (of the 21 subjects, five data sets were rejected due to technical problems and/or subject discontinuation.) All subjects signed an Informed Consent that was approved by the MIT Committee on the Use of Humans as Experimental Test Subjects (Appendix C), as well as by the Ethics Committee of the University of Antwerp Hospital. They were enrolled after being questioned about their medical history. Issues that led to exclusion included a current smoking habit, current orthopedic injuries, known heart conditions, and known vestibular deficiencies. Subjects’ ages were 37.3±9.5 years (average ± standard deviation), heights were 177.7±6.0 cm, weights were 74.7±11.1 kg, and 11 of the 16 subjects described themselves as regular exercisers.
Table 3. Experiment layout. The chronological order is read left to right, top to bottom. G-levels are measured at the heart, along the body axis.

<table>
<thead>
<tr>
<th>Experiment portion</th>
<th>not spinning</th>
<th>0.7-g</th>
<th>1.0-g</th>
<th>1.2- or 1.4-g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 degrees</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 degrees</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 degrees</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Standing on one foot
- Standing on both feet
- Stepping in place

* At 45 degrees, the g-vector creates 0.7-g when the centrifuge is not spinning. Therefore, there was no 0.7-g spin condition.

The experiment (Table 3) consisted of repetitions of the same protocol for four different conditions: upright control, 45° tilt, 21° tilt, and 0° tilt. These correspond to g-gradients of approximately 0%, 30%, 50%, and 80%, depending on body height (Table 4). (We define g-gradient as the difference between the g-level at the feet and the g-level at the head, divided by g-level at the feet. All g-levels are measured along the body axis.) For each of the three tilt conditions, measurements were first taken with the centrifuge static, then while the subject spun at one of three different speeds. The rotation speeds were calculated for each subject, such that the acceleration vector at the level at the heart, along the head-to-feet axis was equal to 0.7-, 1.0-, or 1.2-g. (The acceleration vector along the body was calculated as a vector sum of Earth’s gravity and artificial gravity, as given in Equation 2.) 45° tilt was chosen to provide the smallest g-gradient allowed by the centrifuge. When not spinning, 45° corresponded to 0.71-g along the body axis. 21° allowed for exactly half that (0.36-g along the body axis); therefore, 0°, 21°, and 45° were the chosen tilt angles.

Three subjects were spun to a level of 1.4-g rather than 1.2-g. The protocol was changed after two subjects experienced presyncopal symptoms at 1.4-g.
Table 4. G-gradient corresponding to each g-level and tilt angle. We define g-gradient = (gfeet – ghead)/gfeet.

<table>
<thead>
<tr>
<th>g-level*</th>
<th>0°</th>
<th>21°</th>
<th>45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.77 ± 0.01</td>
<td>0.48 ± 0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0.77 ± 0.01</td>
<td>0.57 ± 0.01</td>
<td>0.24 ± 0.01</td>
</tr>
<tr>
<td>1.2</td>
<td>0.77 ± 0.01</td>
<td>0.60 ± 0.01</td>
<td>0.32 ± 0.01</td>
</tr>
<tr>
<td>1.4</td>
<td>0.76 ± 0.00</td>
<td>0.61 ± 0.00</td>
<td>0.36 ± 0.00</td>
</tr>
</tbody>
</table>

*at heart, along body axis

For each tilt condition and g-level (including the no-spin condition), as well as when the subject was standing upright (tilt=90°), the subject repeated a five-minute sequence. During the first two minutes, the subject stood on his left foot, with the right foot passively hanging between the two force plates (the force plates were mounted on wooden risers, such that the hanging leg was not in contact with any surface). For this portion the subject was asked not to activate his right leg muscles. The subject then replaced his right foot on the force plate and stood evenly on two feet for one minute. For the final two minutes, the subject stepped in place at a frequency of 1.5 Hz, as prompted by a screen before his face. Subjects were allowed to keep their toes in contact with the force plates when stepping to avoid inadvertent leg movements due to Coriolis accelerations. The three portions (one foot, two feet, and stepping in place) will hereafter be referred to as “actions”.

3.2.3 Analysis

Data was sampled at 100 Hz, and downsampled to 50 Hz for ease of processing. Foot forces, heart rate, and systolic and diastolic blood pressure values are an average over the last half of each action time period (the last 30 seconds when standing on both feet, or the last 60 seconds when standing on one foot or stepping in place). Calf volumes are averages over a 5 second interval between seconds 40-45 of each action (this was done to allow comparison between the three actions). Foot forces are simply calibrated values of summed forces from four strain gauges (at each corner of each force plate) and are given as a percent body weight. Calf volumes are given as a percent change of the resting supine value; the liquid strain gauges were calibrated to a “zero” value when the subject was lying supine, legs relaxed, at the beginning of the experiment. Continuous blood pressure was measured at finger level and corrected to heart
level; mean systolic and diastolic values were calculated from the continuous Portapres®
waveform, as was heart rate (beats per minute).

We analyzed foot force, heart rate, blood pressure, and calf volume data by hierarchical
mixed regression. For statistical analysis, we excluded data at tilt=90° (unless specified),
because it was a degenerate case that corresponds to only one g-level. G-level and tilt angle
were considered to be continuous variables, and data from the three subjects who were spun to
1.4-g was included in the statistical analysis and in the figures (note that this sometimes creates
an unexpected effect at 1.4-g). Significance is expressed for p<0.05. For all variables and all
actions, before the model was fit, the residuals were verified to be normally distributed about
zero (not significantly different from a normal distribution about zero, p>0.05, Kolmogorov-
Smirnov test) and the variances of the residuals were verified to be approximately equal (not
significantly different from each other, p>0.05, Levene’s test). Figures and values in the text
give mean ± standard error.

The effect of g-level is given as a slope: that is, the average change in the measure per g-
level (e.g., “beats per minute per g-level”). G-level results were reported in this way because g-
level is considered to be a continuous variable. A higher slope would indicate that the measure is
more sensitive to changes in g-level. Tilt angle is also expressed in this way in Table 6, to
express change in each measure per degree change in tilt.

For calculations related to different body parts, measurements are based on the NASA
STD-3000 anthropometric document (50th percentile male) and are, in percent body lengths from
feet: fingertip, 38%; heart, 73%; eye, 94%; mid-calf, 19%.

3.3 Results

Foot forces increased significantly as g-levels increased. They were significantly higher
for lower tilt angles, when standing on both feet (Figure 14).
Figure 14. Foot forces of both feet added together, expressed as a percentage of body weight. As with all figures, g-level on the x-axis refers to the vector sum of Earth’s gravity and artificial gravity at the subject’s heart level, expressed along the body axis. The significant effect of g-level is shown with a horizontal bracket, and the significant effect of tilt angle is shown with a vertical bracket. As expected, foot forces increase with g-level and decreasing tilt angle. N=15.

The effect of g-level was significant on right calf volume, heart rate, and systolic and diastolic blood pressure, for all actions. In several cases the effect of tilt was also significant, as was the cross effect of g-level and tilt. Results from all physiological measurements are shown in Table 5 and Table 6. Individual subject data is given in Appendix D.
Table 5. Average slopes (value vs. g-level) for four measures. The effect of g-level was significant in all cases.

<table>
<thead>
<tr>
<th>Measure</th>
<th>One foot</th>
<th>Two feet</th>
<th>Stepping</th>
<th>% per g-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Calf Volume</td>
<td>3.5 ± 0.3 (p&lt;0.001)</td>
<td>2.8 ± 0.3 (p&lt;0.001)</td>
<td>2.5 ± 0.2 (p&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Heart Rate</td>
<td>26.9 ± 1.6 (p&lt;0.001)</td>
<td>30.5 ± 2.2 (p&lt;0.001)</td>
<td>12.7 ± 3.3 (p&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Systolic Blood Pressure</td>
<td>18.4 ± 4.2 (p&lt;0.001)</td>
<td>12.1 ± 3.6 (p=0.001)</td>
<td>26.3 ± 4.6 (p&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Diastolic Blood Pressure</td>
<td>17.4 ± 3.3 (p&lt;0.001)</td>
<td>16.5 ± 2.5 (p&lt;0.001)</td>
<td>22.6 ± 3.0 (p&lt;0.001)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Average slopes (value vs. degree of tilt) for four measures. Only significant effects are shown, “n/s” indicates no significant effect.

<table>
<thead>
<tr>
<th>Measure</th>
<th>One foot</th>
<th>Two feet</th>
<th>Stepping</th>
<th>% per degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Calf Volume</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
<td>% per degree</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>-0.41 ± 0.1 (p&lt;0.001)</td>
<td>-0.39 ± 0.1 (p&lt;0.001)</td>
<td>n/s</td>
<td>bpm per degree</td>
</tr>
<tr>
<td>Systolic Blood Pressure</td>
<td>-0.63 ± 0.2 (p=0.001)</td>
<td>-0.45 ± 0.2 (p=0.008)</td>
<td>n/s</td>
<td>mmHg per degree</td>
</tr>
<tr>
<td>Diastolic Blood Pressure</td>
<td>-0.65 ± 0.2 (p&lt;0.001)</td>
<td>-0.62 ± 0.1 (p&lt;0.001)</td>
<td>-0.39 ± 0.2 (p=0.01)</td>
<td>mmHg per degree</td>
</tr>
</tbody>
</table>

3.3.1 Right calf volume

As stated in Section 3.2 (Methods), calf volume was taken to be an average between seconds 40-45. This was an arbitrary choice but used for every subject. It is important to note that the values for the stepping condition are averages of the 1.5 Hz muscular contractions over a five second period. However, the data was surprisingly uniform, so it was used in analysis. Figure 15 gives an example of the calf volume increase over time (excluding calf volume when stepping, since muscular contractions produce much greater effects than increasing gravity levels.)
Figure 15. Time course of calf volume changes for one subject, several tilt angles and actions (in all cases the g-level at the heart is 1.0). Action=0 indicates that the right leg was hanging, action=1 indicates that the subject was standing on both feet. Tilt=90 represents upright testing. There was a problem with data collection for this subject during 40-45s for tilt=90, action=1 and tilt=0, action=1. In all cases, the time when the subject began each action is set to time=0.

There was a main effect of g-level and action on right calf volume. Specifically, volume significantly increased with increasing g-level (2.9±0.2% per g-level over all actions). Over all data, the one foot case resulted in higher calf volumes than the two foot case, which resulted in higher calf volumes than when the subject was stepping in place (45° tilt angle example, Figure 16). The cross effect of tilt and g-level was also significant.
Figure 16. Right calf volume (45° tilt angle only), showing the effect of action.

Data was analyzed separately for each action. The effect of g-level was significant for all actions, but the effect of tilt was not significant for any action. The greatest change per g-level occurred when the subject’s right leg was hanging with no muscular activation: 3.5±0.3% per g-level.

Figure 17 and Figure 18 show right calf volume both as a function of g-level at the heart, and g-level at the calves (calf g-levels averaged to give one value per g-level at the heart, per tilt angle).
Figure 17. Effect of g-level and tilt angle on right calf volume when (a) standing on one foot, (b) standing on two feet, and (c) stepping in place. These are with respect to g-level at the heart. Significant effects of g-level are shown with horizontal brackets, and significant effects of tilt angle are shown with vertical brackets. The legend is given in the lower right hand corner. Volume increases with increasing g-level and decreasing tilt angle. N=14.
Figure 18. Effect of g-level and tilt angle on right calf volume when (a) standing on one foot, (b) standing on two feet, and (c) stepping in place. These are with respect to g-level at the calves. The legend is given in the lower right hand corner. N=14.
3.3.2 Heart rate

There was a significant main effect of g-level, tilt, and action for all heart rate data. On average, heart rate increased $23.0 \pm 0.7$ beats per minute per g-level, and increased significantly with decreasing tilt angles (increasing g-gradient). The one foot condition resulted in higher heart rates than the two foot condition, which resulted in heart rates higher than when stepping in place. The cross effect of tilt and g-level on heart rate was also significant.

Data was analyzed separately for each action. The smallest change per g-level was found when the subject was stepping in place: $12.7 \pm 3.3$ beats per minute per g-level, as opposed to $26.9 \pm 1.6$ and $30.5 \pm 2.2$ beats per minute for one foot and two feet, respectively. Stepping in place also removed the significant effect of tilt, which was present for both the one foot and two feet conditions. See Figure 19.

Stepping in place, then, resulted in an overall lower heart rate than the other two actions, as well as a smaller slope, and removes the significance of tilt angle.
Figure 19. Effect of g-level and tilt angle on heart rate when (a) standing on one foot, (b) standing on two feet, and (c) stepping in place. Significant effects of g-level are shown with horizontal brackets, and significant effects of tilt angle are shown with vertical brackets. Heart rate increases with increasing g-level and decreasing tilt angle, except when stepping in place, which decreases or removes both effects. N=16.
3.3.3 Arterial blood pressure at heart level

There was a significant main effect of g-level, tilt angle, and action on systolic and diastolic blood pressure. On average, systolic blood pressure increased 19.3±2.4 mmHg per g-level and diastolic blood pressure increased 19.1±1.7 mmHg per g-level (although pulse pressure was not explicitly analyzed, it appears to have been unchanged by g-level). Both systolic and diastolic blood pressure increased significantly with decreasing tilt angle. When stepping in place, systolic and diastolic blood pressure were both significantly higher than the average of all actions, whereas when standing on both feet, they were significantly lower. The cross effect of tilt and g-level was significant for systolic and diastolic blood pressure.

Data was analyzed separately for each action. The greatest blood pressure change per g-level was found in the stepping condition. Tilt significantly affected blood pressure in all cases except for systolic blood pressure when stepping in place. As tilt angle decreased, blood pressure increased. See Figure 20.

We find generally higher systolic and diastolic blood pressure when stepping in place, and generally higher blood pressure for lower tilt angles.
Figure 20. Effect of g-level and tilt on systolic (upper traces) and diastolic (lower traces) blood pressure at heart level, when (a) standing on one foot, (b) standing on both feet, or (c) stepping in place. Significant effects of g-level are shown with horizontal brackets, and significant effects of tilt angle are shown with vertical brackets. Blood pressure increases as g-level increases and tilt angle decreases. N=16.
Chapter Four

Experiment 2: Effectiveness of stair-stepping during centrifugation

4.1 Introduction

As discussed in Chapters One and Two, exercise during centrifugation is a proposed countermeasure to the physiological deconditioning that occurs due to long-duration spaceflight. This combination is suggested in order to improve upon current exercise-only countermeasures, which have not been sufficiently effective [4]. Although it has not been used in spaceflight, artificial gravity through centrifugation can produce an acceleration vector parallel to the body axis, and as such, evokes very similar physiological responses to standing in Earth’s gravity. Exercising while in this artificial gravity field is likely to produce effects that are systemically more similar to exercising on Earth than current microgravity exercise, which typically uses bungee cords to load the subject axially but results in no redistribution of fluid.

The problem of combining exercise with artificial gravity has been framed as follows: previous studies have established that exercising on a centrifuge is feasible and produces a stimulus consistent with an effective spaceflight countermeasure [10, 49, 51, 106, 108, 109, 111, 112, 114, 115]. There has been some evidence, also, of its effectiveness against bedrest deconditioning [10, 49, 51, 109]. A recent study at the University of Texas Medical Branch indicates that centrifugation with 2.5-g at the feet may be effective in protecting cardiovascular function and muscle performance [103]. However, no study has thus far looked at the long-term
effects of exercising on a centrifuge for healthy, mobile subjects. Additionally, previous studies have looked almost solely at cycle ergometry as the mode of exercise [10, 49, 51, 106, 108, 109, 111, 112, 120], with only two studies to this author’s knowledge that implement squats [114, 115]. No study thus far has looked into any version of walking or stepping exercise.

In this study, we have attempted to characterize the effectiveness of stair-stepping on a short-radius centrifuge in terms of fitness benefits.

4.1.1 Hypotheses

_Hypothesis 2.A. Subjects will be able to complete eight weeks, three times per week of exercise (20-40 minutes duration) using a stair-stepper on a short-radius centrifuge, with little or no discomfort._

We aim to provide an exercise environment on the centrifuge that will allow subjects to exercise comfortably and normally for an eight week exercise program.

_Hypothesis 2.B. Aerobic fitness will improve as a result of eight weeks of stair-stepping exercise on a centrifuge._

We aim to improve aerobic fitness by enrolling subjects in an eight week exercise program on the centrifuge. Aerobic fitness will be improved by gradually increasing the intensity and duration of the exercise sessions.

_Hypothesis 2.C. Quadriceps strength and push-ups endurance will improve as a result of eight weeks of stair-stepping and arm exercise on a centrifuge._

We aim to improve strength by exercise on the centrifuge. Stair-stepping exercise primarily targets the quadriceps, while resistance band arm exercise should increase arm strength.

_Hypothesis 2.D. Body composition will improve (decreased body fat percentage, increased bone mineral content) as a result of eight weeks of stair-stepping on a centrifuge._

Improvements in physical fitness, including aerobic fitness, strength, and endurance, will generally result in improved body composition over some period of time. We aim to improve body composition by decreasing fat percentage. We also aim to improve bone mineral content
through repetitive high-resistance stepping exercise, as bone loss is of primary concern for spaceflight.

**Hypothesis 2.E. Neither balance nor orthostatic tolerance will change as a result of an eight week exercise program of stair-stepping on a centrifuge.**

Vestibular disturbances while exposed to centrifugation can generally be mediated by holding the head at a constant angle; regardless, there should be no long-term changes in balance due to eight weeks of exercising on the centrifuge.

### 4.2 Methods

This study protocol was approved by the MIT Committee on the Use of Humans as Experimental Subjects, and all subjects signed an Informed Consent (Appendix C).

#### 4.2.1 Subjects

Eight male volunteers participated in the experiment. They were recruited by posters displayed on campus (Appendix E). They were selected if they reported no health problems as determined by health questionnaires (Appendix E), had not been part of a regular exercise program for at least one year, and if an initial treadmill screening test (see below) did not reveal a maximum oxygen uptake ($V_{O_2}$-max) of greater than or equal to 42.4 mL/min/kg [123]. This value is an approximate cutoff for males of ages 20-29, between “fair” and “good” aerobic condition. We chose individuals with low aerobic fitness because they were more likely to improve after a short period of time [124]. The decision to choose unfit subjects immediately sets these subjects apart from the astronaut population, whose members are highly fit. Parallels may be drawn between the unfit subjects of this study, and astronauts who become unfit due to long-duration spaceflight. However, it should be noted that previously fit subjects who have become unfit tend to see improvements more quickly than long-term sedentary subjects [124], so comparisons between a deconditioned astronaut population and the subjects of this study should be made carefully. In addition to the eight data sets obtained, one other subject completed four weeks of the exercise program before voluntarily terminating (discussed in Chapter Five), and three pilot subjects preceded the formal experiment (Section 4.2.5).
Average age of subjects was 25.2 (range 19-28), average height was 175.9±5.1 cm, average weight was 77.5±7.1 kg, and an average body mass index (BMI) of 25.1±2.8 kg/m² (the average BMI of men aged 20-29 is 26.6±0.2 kg/m², based on 1999-2000 statistics [125]).

4.2.1.1 Single-sex justification

We chose to restrict our study to males due to some evidence of differences in aerobic training ability and/or strength measurements in men and women, specifically due to periodic changes with the menstrual cycle. In a study of young women over six months (regularly menstruating, characterized as oral contraceptive users or not), the maximum voluntary force of the adductor pollicis (the muscle in the hand which serves to adduct the thumb) increased and decreased in accordance with the menstrual cycle (these subjects were compared with male control subjects [126]). In general, aerobic measurements during a graded maximal treadmill test do not seem to vary with menstrual cycle (e.g. $\dot{V}O_2$-max and time to exhaustion), but the point at which subjects reach ventilatory threshold (the inflection point at which ventilation increases steeply) did vary among phases in the menstrual cycle [127]. Jurkowski et al [128] found that aerobic performance tended to be constant throughout the menstrual cycle, with the exception of performance of high-intensity exercise, as well as lactate production, which did vary over the cycle. Metabolic responses to exercise (as measured in a controlled treadmill test) also do not appear to vary with the phase of the menstrual cycle, unless the subject’s nutritional regime was unusual (for this study, fasting). In this case, blood samples yielded unexpected results (response patterns of insulin, growth hormone, and free fatty acids to exercise) for different phases of the cycle [129]. Basal metabolic rate also fluctuates with the phase of the menstrual cycle, as evidenced in a 92-day study of six women in a controlled-diet setting [130].

4.2.2 Experimental protocol

The subjects participated in an eight week exercise program, during which they exercised three times per week on the MIT Short-Radius Centrifuge. Before and after the exercise program, and after four weeks, they underwent a series of measurements to determine their level of fitness. These measurements took place in three locations: in the Man-Vehicle Laboratory, at MIT’s fitness center, and at the MIT Clinical Research Center. We attempted to schedule all
measurement sessions at the same time of day as previous measurement sessions of the same type.

4.2.2.1 Measurement sessions

In-lab measurement sessions

In-lab measurements included a treadmill oxygen uptake test, an upright stepping test, a balance test, a quadriceps maximum force extension test, and leg circumferences. The treadmill test was additionally performed once before the beginning of the study for each potential subject, in order to test whether or not they had a low enough $\dot{V}_{\text{O}_2}$-max to qualify as a subject (thus, it was performed a total of four times for the study participants). This additional pre-screening measurement further allowed us to confirm that fitness did not change between their pre-screening and their first measurement session.

Treadmill oxygen uptake test. The treadmill used for maximal oxygen uptake ($\dot{V}_{\text{O}_2}$-max) testing was a Trotter CTX-plus® (Cybex, Medway, MA). It allowed for running speeds of up to 12.9 km/hr (8.0 mi/hr) and grades of up to 10%. Subjects were instrumented with a gas analyzing face mask unit (VO2000® face mask unit, MedGraphics, St. Paul, MN), and a heart rate monitor (Acumen TZ-max 100®, Bedford, MA). They warmed up for three minutes, increasing speed as desired, until they reached a jogging speed that they believed would exhaust them in 10-15 minutes (for tests subsequent to the first test, they increased the speed to the same speed as they had chosen for the first test). Upon reaching this speed, they ran for two minutes, and reported their Borg rating of perceived exertion (RPE4, [131]). The treadmill grade was then increased to 2%. They continued running for two more minutes, reported their Borg RPE, and the treadmill grade was increased to 4%. This continued (increasing grade by 2% every two minutes, speed constant) until the subject’s heart rate reached 200-Age (a minimum criterion for maximum effort, see [132, 133]) or until the subject had completed two minutes of running at 10% grade, whichever came first. See Figure 21.

---

4 The ratings are as follows and refer to total perceived exertion, not that localized to the muscles being used (legs, in this case). On a scale of 6-20, 7=Very, very light, 9=Very light, 11=Fairly light, 13=Somewhat hard, 15=Hard, 17=Very hard, and 19=Very, very hard.
\( \dot{V}_{O_2} \)-max was extrapolated from this data: a line was fit to the heart rate versus oxygen uptake graph, and a nomogram was used to estimate maximal oxygen uptake [134]. The Astrand nomogram was deemed acceptable for \( \dot{V}_{O_2} \)-max estimation because the relationship between heart rate and oxygen uptake is fairly linear except at high work loads. For this reason, the nomogram tends to underestimate \( \dot{V}_{O_2} \)-max, particularly for untrained people (error up to 15%) – however, since subjects were used as their own controls and thus absolute \( \dot{V}_{O_2} \)-max was not required, this was considered acceptable. Subjects were all approximately the same age, so that did not affect reliability of the measurement, and subjects were not exposed to heat, also known to affect the measurement. Additionally, the length of the test was closely regulated, so that exhaustion did not affect the results. A true maximum test was not used because, as subjects were not athletically fit, it was deemed potentially unsafe to stress them to their maximum exercise capacity. The linear relationship between heart rate and oxygen uptake (\( \dot{V}_{O_2} \)) as the test progressed was also of interest: we would expect that both the slope and the intercept of the heart rate vs. \( \dot{V}_{O_2} \) relationship would decrease as subjects became more fit [135] – that is, as \( \dot{V}_{O_2} \) increased, heart rate would increase less as the subject becomes more fit; also, for the same \( \dot{V}_{O_2} \), heart rate would generally be lower as the subject becomes more fit.
Figure 21. Subject during the treadmill maximal oxygen uptake test. The subject is wearing the VO2000® face mask unit and a chest strap heart rate monitor (not visible under the subject’s shirt).

Upright stepping test. An upright stepping test included a warm-up, two minutes of constant cadence exercise, two minutes of constant heart rate exercise, two minutes of maximal stair-stepping, and four minutes of rest. Measures for this test were heart rate (Acumen TZ-max 100® chest strap monitor), beat-to-beat blood pressure (Portapres® model 2.0 unit), foot forces (modified digital bathroom scales mounted to each stepper foothold), and respiratory parameters including oxygen uptake, ventilation, and breathing rate (VO2000® face mask unit). Blood pressure measurements included mean blood pressure, which is the true arithmetic mean pressure between upstrokes, and systolic and diastolic pressures, which are the maximum and minimum pressures during the pulse beat, respectively. Systolic and diastolic pressures were calculated after the test session, using the pressure waveform output and a peak detection algorithm developed in-house using Matlab (Section 4.2.3). For the constant cadence portion, the subject chose a comfortable stepping rate in the first session and used the same cadence for every measurement sessions; this cadence was also used for the four-minute warm-up period before testing began. The constant heart rate was chosen to be 50% heart rate reserve (HRR). HRR is determined by:
\[ X\% \text{ HRR} = X\% \times (\text{Maximum Heart Rate} - \text{Resting Heart Rate}) + \text{Resting Heart Rate} \]

Equation 4

The resting heart rate in the above equation was determined after three minutes of supine rest before the upright stepping test, and the maximum heart rate was estimated as 220-Age. For the two-minute maximal stair-stepping portion, the subject was instructed to “try to do as many steps as you can in two minutes”. He was given notification when he had one minute, thirty seconds, and ten seconds left of stepping. At the end of two minutes, he sat in a chair next to the stepper, and rested for four minutes while measurements continued. See Figure 22.

![Figure 22. Subject during the upright stepping test. The laptop used to measure respiratory parameters is in the foreground. The subject is wearing the VO2000® face mask unit. The black belt (battery unit), and wrist unit and finger cuff on his left hand are the Portapres® blood pressure monitoring system; the data from this system was recorded by the centrifuge computer (centrifuge visible in left hand side of photograph).]

Balance. A Sharpened Romberg test [136] was used to measure balance. Subjects stood heel-to-toe with their hands crossed above their chest, closed their eyes, and attempted to hold that position without faltering for 60 seconds. If the first attempt was not successful, the subject repeated this test two more times. See Figure 23.
Figure 23. Subject doing the Sharpened Romberg test. Tape on the floor allowed him to line up his feet. The subject attempted to hold this position for 60 seconds.

Quadriceps maximum force extension test. A maximal quadriceps extension test against a force plate allowed for a measure of leg strength. The subject sat in a chair that was fixed rigidly to a Unistrut® frame, which was pushed against a wall. The chair was covered with a yoga mat to prevent slippage. The stepper was placed against the wall to act as a force plate. The subject was instructed not to push against the back of the chair (this was verified visually), although he was allowed to grip the sides of the chair with his hands. For the test, he placed the ball of his right foot against the stepper such that his upper leg was extended slightly beyond 90°, and slowly extended to maximum force over a period of approximately 5 seconds. After a rest period of his chosen duration (usually 15-30 seconds), he repeated the test twice (with a rest in between), for a total of three maximal tests. See Figure 24. The peak force achieved during each test was determined by the experimenter during analysis, and the greatest of the three values was used for statistical tests.
Figure 24. Subject doing the maximal quadriceps extension test. The subject did not push against the chair back during the test.

Leg circumferences. The subject’s leg circumferences were measured at approximately the base of the soleus and the thickest part of the gastrocnemius (as measured at 1/3 and 2/3 of the distance from the ankle bone (lateral malleolus) to the top of the tibia), and approximately 1/4 of the distance from the center of the patella to the hip. The height of each of these locations was recorded and kept constant for week 0, 4, and 8 measurements. These measurements were taken with the subject standing upright, evenly on both feet.

Clinical Research Center measurement sessions

Clinical Research Center (CRC) measurements included resting vital signs, resting energy expenditure, an orthostatic stand test, a full-body dual x-ray absorptiometry (DXA) scan (QDR-4500®, Hologic Inc, Bedford, MA), and skinfold and circumferences tests.

Resting vital signs. Subjects’ body temperature, sitting blood pressure, pulse rate, height, and weight were recorded at the beginning of the session. These parameters were measured for baseline health. Only body weight, which was measured with the subject wearing a light gown and having fasted since the night before, was used in analysis.
Resting energy expenditure. The resting energy expenditure (REE) test measured resting respiratory and metabolic parameters for the subject: $\dot{V}_{O_2}$, METS (metabolic equivalent, in kcal/kg/hr), carbon dioxide expiration ($\dot{V}_{CO_2}$), minute ventilation, respiratory quotient, and REE, measured as projected kilocalorie usage per day. The test began after the subject lay supine for 25 minutes (awake; he was checked periodically by the nurses). After this rest period, the subject continued to rest for 20 minutes while measurements were taken. A clear plastic hood was placed over the subject’s head so that expired gases could be measured and recorded on the nearby computer (Figure 25). The subject was not permitted any entertainment during the test, as resting parameters are very sensitive to physiological reactions. The measurement value of each parameter was an average over the last 15 minutes of the test.

Orthostatic stand test. Orthostatic tests using tilting tables are useful diagnostic tools for patients who experience hypotension or presyncope upon standing [137]. Because we had no reason to expect any changes in orthostatic tolerance, we instead performed a simple stand-test in which the subject gradually went from the supine to standing position, of his own accord. This test allowed for a very basic measure of orthostatic responses. Stand-tests have been used extensively in post-spaceflight testing [14].

After 45 minutes of supine rest for the REE test, subjects’ blood pressure and heart rate were measured. They were then asked to sit up of their own accord; their blood pressure and heart rate were again measured after three minutes in this position. They then stood up, and after three minutes, blood pressure and heart rate were measured (Figure 26).
Figure 25. Resting energy expenditure. Subject lies supine with a plastic hood placed over head to capture and measure expired gases.

Figure 26. (Left to right.) Subject supine, sitting, and standing for the orthostatic stand test. The nurse manually measured and recorded his blood pressure.

Full-body DXA scan. A full-body DXA scan (Figure 27) measured body composition: lean, fat, and bone mineral content, and relative percentages and densities. The QDR-4500® model measures body composition using a multidetector array and switched pulse dual-energy x-ray tube, within approximately 1.0% error. The body was divided by segment for measurements: head, trunk, arms, and legs; the pelvis and lumbar area were also targeted for bone measurements. The radiation dose of the DXA scan, 0.26 µrem, is less than 10% of the annual natural background radiation from the Earth and sky, producing no known health risks.
Figure 27. The dual x-ray absorptiometry (DXA) scan measured body composition. The extension over the subject passed over his body several times while he lay still. The scan lasted approximately 5 minutes.

**Skinfold and circumferences tests.** CRC nurses measured the skinfold thickness of the subject at his triceps, biceps, subscapular region (upper back), and suprailiac region (trunk), as an estimate of body fat content. They also measured mid-arm, mid-thigh, and mid-waist circumference. They measured the waist width at the iliac level and the widest level in order to obtain a waist-hip ratio. Lastly, they measured elbow width to obtain an estimate of skeletal frame size (Figure 28).
Z-center fitness assessments

The Z-center fitness assessment was a basic test battery performed by a trainer at the MIT athletic facilities. These fitness assessments are available to any fitness center patron, and were intended to be mostly redundant measures for the subjects. All fitness assessments were performed by the same trainer.

The fitness assessment included resting heart rate and blood pressure (measured in the sitting position), body weight, skinfold measurement (chest, abdomen, thigh) and the corresponding estimate for percent body fat, a cycle ergometer aerobic conditioning test, a full-body push-ups test, and sit-and-reach flexibility. The sit-and-reach flexibility test required the
subject to extend his legs in front of him while sitting on the floor, with heels approximately shoulder-width apart, and bend at the waist to extend his fingertips between his heels.

The cycle ergometer aerobic conditioning test required that the subject pedal at a constant cadence on a stationary bicycle. The bicycle resistance was gradually increased, which increased the work rate of exercise. During the test, the subject’s heart rate was measured. These two measures (work rate and heart rate) allowed for an estimate of $\dot{V}_O_2\text{-max}$, using standard methods [138]. The full-body push-ups test was simply the number of full-body push-ups the subject could do without rest, to exhaustion.

### 4.2.2.2 Exercise sessions

The exercise equipment included a Kettler Vario® mini-stepper (Redditch, Worc, UK), which was mounted vertically on a surface at the subject’s feet [116]. The stepper uses hydraulic dampers as resistance to stepping. When the subject steps, he has a limited range of motion, and usually bottoms out at the stoppers. For this reason the subject experiences an impact load on his foot during each step. The stepper was instrumented with force plates (modified digital bathroom scales). Additionally, resistive arm bands (Power-Systems Premium Versa-Tube®, Knoxville, TN) were mounted to the surface of the centrifuge, allowing for arm exercise (see Appendix A for information on the mount). Subjects could choose among four resistance levels of these bands, and used them in varying motions.

#### Background on the use of a stair-stepper

Previous authors have characterized upright stair-stepping as an (upright) exercise modality. In a study to quantify subjective exercise intensities, experimenters enrolled subjects in three modes of exercise tests (randomized order): stair-stepping, cycle ergometry, and treadmill exercise. For each type of exercise test, the subject was allowed to adjust the intensity of exercise as desired. Over the 20 minute test, subjects increased their heart rate significantly more for both stair-stepping and cycle ergometry than for treadmill exercise, although the Borg RPE was not different (average ratings of 12-13 for all modes of exercise [139]).

In a test comparing stairclimbing (slightly different from the stair-stepper used here, as the subject must lift his foot to place it on the next step) with treadmill exercise, subjects underwent a graded protocol that required approximately the same work rate per grade for both
the treadmill and the stairclimbing exercise. For the less strenuous exercise grades, stair-stepping required greater heart rate and oxygen consumption than treadmill exercise. The authors suggest that stairclimbing should be considered at least as a feasible mode of exercise training or testing [140]. In a different test that controlled power output carefully, there were no differences in heart rate or oxygen consumption responses between cycling and stairclimbing [141].

Using typical fitness equipment (n=33), stair-stepping results in EMG activity between 12% and 53% maximum voluntary isometric contraction (MVIC) in the gluteus maximum, rectus femoris, vastus medialis, and gastrocnemius (Figure 29). Significantly higher muscle activity during the knee extension phase was found for higher stepping cadences, with the highest muscle activity found for the rectus femoris and vastus medialis [142].

Exercise Session Protocol

Subjects scheduled exercise sessions at their convenience, three days per week. They were advised to try to schedule sessions 2-3 days apart, if possible, but were allowed to schedule sessions whenever they were able.

Upon arrival, subjects sat a in a chair for several minutes before resting (sitting) heart rate and blood pressure were taken using a Vernier® (Beaverton, OR) standard automatic cuff (oscillometric method of pressure calculation). They were also weighed, wearing their exercise clothes, including shoes.

The subject lay down on the centrifuge. A portable DVD player with a movie of the subject’s choice was mounted to the centrifuge above his face; the subject wore earphones to hear the movie. The heart rate monitor’s wristwatch receiver was mounted next to the DVD player, so that the subject could monitor his heart rate. The subject was also responsible for starting and stopping the heart rate recording, as the wristwatch receiver was able to record an average heart rate value over a designated period of time. The footplate was adjusted to the subject’s height, and Versa-Tube® resistance bands for arm exercise were attached to the centrifuge backslider, which was held in a fixed position for the exercise sessions.

Exercise sessions were 20 minutes (first week), 30 minutes (weeks 2-4), and 40 minutes (weeks 5-8) long. The American College of Sports Medicine recommends exercise 3-5 days per week for 20-60 minutes, with duration adjusted inversely with intensity [143]. After spinning up the centrifuge, the subject warmed up for 3 minutes at a self-determined pace, and was then asked to increase his heart rate to the target level (see below) assigned by the experimenter. Timing for the session began when he reached this level, and the heart rate recording also began at this time. The subject maintained his target heart rate by stepping faster or slower, or using higher resistance arm-bands (which could only be changed between sessions). Thus, the choice of increasing arm or leg work to increase heart rate was left to the subject. (Subjects reported that they tended to exercise as fast as they could with their legs, and used arm exercise to increase heart rate the rest of the way to the target level.) Halfway through the session, the subject was asked his Borg rating of perceived exertion. For the last two minutes of the exercise session, the subject stopped the heart rate recording, and cooled down at his own pace. The centrifuge was then decelerated and the subject was helped off the centrifuge. He was given a bottle of water and a towel, and asked to stretch before leaving.
During the exercise sessions, the centrifuge was spun at 30 RPM. A previous study on the MIT centrifuge revealed that cardiovascular parameters were more similar to upright for the 1.5-g case than for 1.0-g or less, where g-level is measured at the feet [144]. Generally 30 RPM gives slightly higher than 1.5-g at the feet, measured along the body axis (1.6- to 1.8-g for subjects between 165 and 182 cm height). The centrifuge was spun in opposite directions on alternate sessions (clockwise and counterclockwise), in order to balance the lateral displacement effect of Coriolis forces on the knees and hips. For the subject’s comfort, the room was completely dark during exercise sessions, except for the DVD player and a small reading light by which the subject could read the heart rate display.

The subject exercised at target heart rates between 40-55% HRR. These heart rates were loosely scheduled to increase by 5% HRR between weeks 1 and 2, 3 and 4, and 6 and 7, but were actually increased to the next level during the session after a subject gave a subjective Borg rating of 11 or lower (whenever that occurred). This was done in an attempt to maintain average ratings of 13-15. In general, values of 50-85% HRR are required to maintain or improve aerobic and cardiovascular fitness, although subjects with very low aerobic capacity may see improvements with levels of 40-49% HRR [143]. Initially we intended to require the higher heart rate levels (e.g. 50-65% HRR), but the lower heart rates were chosen after pilot subjects had difficulty increasing their heart rate to levels higher than 55% HRR.

Aside from heart rate and Borg rating, the only other measurements taken during exercise sessions were the peak foot force attained during each step, and step displacement. Specifically, for every step on the stair-stepper, peak force (which usually occurred when the stepper “bottomed out”) was determined during post-processing. Then, the peak forces for all of the steps during the exercise sessions were averaged for each foot. Thus, after post-processing we had an average and standard deviation of the peak foot forces for each foot, over that particular exercise session.

4.2.3 Data post-processing

An analysis package was developed to summarize data collected by the onboard computer from each exercise session and the upright stepping test of the in-lab measurement session. Data recorded by the onboard computer included the Portapres® waveform and mean blood pressure, foot forces, and stepping displacement (potentiometer). The software package
allowed the investigator to choose the “start” and “end” time for each analysis run, or multiple “start” and “end” times. Therefore, for the upright stepping test, we could find an average measurement value between, e.g., minutes 2 and 4. For the exercise sessions, the average measurement value spanned the 20-40 minute exercise period. All data was acquired as voltage and converted to appropriate units using values obtained from manual calibration (foot forces, potentiometer) or published data (Portapres®).

The analysis package had the following capabilities:

- For each foot force plate’s voltage output, the peak force per step was found. These values were binned, and the output included the average peak force and standard deviation for each foot, over the specified time period (for exercise sessions, this time period generally began after warm up and ended immediately before cool-down). Additionally, the average force per step (average of the force plate values over the full step) was obtained for work rate measurements, described below.

- The stepper potentiometer gave displacement per step; that is, how far the subject stepped. The output was simply the displacement over each step, but this was multiplied by the average force per step to give work rate per step. The output, then, was average and standard deviation of work rate for each foot, over the specified time period.5

5 This method contains some error, but was used in order to reduce computational time for the very large data files (1000 samples/second for over 40 minutes). In order to obtain the precise value of work per step, we would have had to use the equation $W = \int_{x_1}^{x_2} Fdx$, where $W$ is work, $F$ is force, $x$ is distance, and $x_1$ and $x_2$ are the distance limits of each step. To solve this equation, we would have had to fit a function to $F$ over each step the subject took, and solved this integral, which is computationally very demanding. We have fit a curve separately to one step and found the exact work value, in order to illustrate the error in our approximation method.
• The stepper potentiometer also allowed us to deduce the timing of each step. The time stamp of each left-to-right transition detected by the potentiometer was binned, and the period between each time stamp was calculated. From this, we calculated the cadence of stepping. The output from our analysis package included average and standard deviation of stepping cadence, over the specified time period.

• Portapres® data gave a pulse pressure waveform. This was analyzed for its cyclic minimums and maximums, which correspond to diastolic and systolic blood pressures, respectively. We obtained a diastolic and systolic value for each pulse wave, and the output was the average and standard deviations of these values, over the specified time period.

• Portapres® data also gave a mean pressure. This was not a waveform, simply a value calculated by the unit. The output from our software was the average mean pressure over the specified time period.

4.2.4 Statistical analysis

Statistical analysis was done using repeated measures analysis under a general linear model (GLM); thus, each subject acted as his own control. The residuals of variables were verified to be normally distributed about zero (p>0.05, Kolmogorov-Smirnov test), before a GLM was fit to the data with “week” as the repeated measures variable. If a GLM could be appropriately fit (p<0.05), the effect of week was considered to be significant, and further hypothesis testing revealed specific differences between weeks 0 and 4, 4 and 8, or 0 and 8. The subject who completed only four weeks was excluded from statistical tests, but is shown in the figures for comparison. No outliers were removed, due to the small number of subjects.

4.2.5 Pilot experiment

The initial three subjects were evaluated periodically over a six month period, and only one of these subjects completed eight weeks. One subject exercised on the centrifuge, and two

The figure above shows actual data (290 data points) from one step: force (measured by the force plates) and distance (measured by the potentiometers). By fitting a polynomial to the data points and integrating, we find a work value of 50.4 N-m. The method that we used in our post-processing, in which the average force was multiplied by the distance, yielded a value of 45.2 N-m, which is an error of 11%.
of the pilot subjects exercised upright (one of these was the eight week subject). No data from these sessions was used in analysis. The purpose of the pilot subjects was to allow us to refine the study protocol, hardware selection and placement, and address any discomforts or complaints that the subjects had. Three major modifications were made due to pilot subject reports: we refined the footplate placement, refined the length of the study, and modified the instrumentation to eliminate ECG recording (3-lead ECG, Criticare® 504-US, Waukesha, WI).

The first pilot subject exercised on the centrifuge primarily to aid in hardware modifications necessary for the study. This subject experienced lower back pain after several exercise sessions, and the exercise sessions evidently exacerbated the problem. Upon examination, it was apparent that the back of the subject’s heels were approximately 6 cm below the plane of the subject’s back. In normal stance, the heels are approximately in plane with the back; for comfortable repetitive exercise (e.g. cycling, upright stair-stepping) the heels are at or in front of the plane of the back. As a result of this observation, the footplate was adjusted and the stair-stepper was moved up, so that the subject’s heels rested approximately 8 cm above the plane of the subject’s back. The pilot subject in question was able to continue the exercise program after this adjustment.

The second and third pilot subjects exercised upright on the stair-stepper for comparison purposes. Initially, we intended to enroll subjects in a four-week study, with half of the subjects experiencing centrifuge exercise, and half experiencing an identical exercise stimulus, but upright. Centrifuge subjects could be compared with upright subjects, and it was hypothesized that there would be no differences in the fitness improvements seen in each group. One of the upright subjects followed the experimental protocol closely (three sessions per week, 20-40 minute sessions at a target heart rate, and measurement sessions as described above). After four weeks, very minor fitness changes were apparent. As a result, we extended the length of the study to eight weeks and continued the subject in the exercise program. With this increased study length, we eliminated the upright exercise group, with the intention of using subjects as their own controls (before/after fitness benefits). To compare with upright exercise, then, we rely on existing literature.

A minor change was also made after the first of the nine experimental subjects. We found that in this subject, the ECG (used to measure heart rate) posed several problems, the greatest of which was that often the signal dropped out, usually due to slippage of the electrode
due to perspiration from exercise. The ECG system required the subject to wear three electrodes on his chest for every session (which also resulted in minor skin irritation). The advantage of this system was that, with later analysis of the data, we could calculate average heart rate for any portion of the exercise session. However, it was determined that the only real requirements for heart rate measurement during exercise were (1) the subject must be able to monitor his heart rate during sessions, and (2) the subject’s average heart rate during the exercise session (excluding warm-up and cool-down) must be recorded. Additionally, the Committee for the Use of Humans as Experiment Subjects did not require the use of an ECG. We therefore replaced the 3-lead ECG with a simple Acumen TZ-max 100® chest strap heart rate monitor, and wristwatch receiver, as previously described. The receiver allowed for recording of a specified portion of the test session, which the subject activated after the warm-up period, and stopped before cool-down, as outlined above. This heart rate monitor did drop out occasionally during the exercise sessions, but if that occurred, the data was not recorded in the final average value.

4.3 Results

In the main experiment, subjects reported no discomfort, other than exercise fatigue, when exercising on the spinning centrifuge. One subject dropped out after the measurements at week 4, due to reported headaches later in the day of his exercise sessions. Timing of all subjects’ sessions is shown in Figure 30. Note that we allowed “pre” measurements to be much earlier than the first exercise sessions, if the subject’s schedule was restrictive.
All exercise and measurement sessions

Figure 30. Schedule of all measurement and exercise sessions, for all subjects. Day 0 is designated as the first exercise session. Subject 7 terminated after four weeks. Subject 9 performed the 8-week treadmill test twice, since the first test yielded questionable data. The screening test, which just included the treadmill test and is designated as a red circle, was allowed to be performed any amount of time before the start of the study.

4.3.1 Exercise sessions

During the exercise sessions, subjects were able to maintain their heart rate within 4% of the target on average, while maintaining an average rating of perceived exertion of 12.9 (between 11 = “fairly light” and 13 = “somewhat hard”). See Figure 31a. Peak foot forces during exercise, averaged over all exercise sessions, were 45% to 124% of body weight, depending on the subject; the overall average among subjects was 83% body weight (Figure 31b).
Figure 31. (a) Borg ratings of perceived exertion during exercise sessions. (b) Peak foot forces, as a percent of body weight, during exercise sessions (each session has one average value), and the inset shows a typical force profile of one foot. Box plots show median value, first and third quartiles, and minimum and maximum values. Outliers that are greater than 1.5×(interquartile range) are shown as stars, and greater than 3×(interquartile range) are shown as open circles. Each subject is given his own box plot that summarizes all of his exercise sessions.

4.3.2 Aerobic changes

The upright stepping test indicated some aerobic fitness changes (Table 7). Specifically, during two minutes at constant cadence, respiration rate, minute ventilation, and ˙\( V_\text{O}_2 \) decreased from weeks 0 to 4 to 8, although none of them significantly. During two minutes of constant heart rate exercise, cadence increased significantly (Figure 32). For the maximum step test (in which the subject attempted to step as many times as possible in two minutes), the number of steps significantly increased, as did the heart rate and minute ventilation achieved in the last 30 seconds of the test. Heart rate and minute ventilation were significantly higher one and two minutes after cessation of exercise, compared with previous measurement sessions.

The estimated ˙\( V_\text{O}_2 \)-max obtained from the treadmill test yielded no significant changes. Looking instead at the heart rate vs. ˙\( V_\text{O}_2 \) relationship for each treadmill test, we found moderate decreases in the slope of those subjects (n=5) whose data could reasonably be fit to a line (r² > 0.80). An example of the heart rate vs. ˙\( V_\text{O}_2 \) relationship at weeks 0, 4, and 8 is shown in Figure
36. Also note that an increase $\dot{V}_{O_2}$ at a given work rate would be expected as subjects become more fit [135].

Table 7. Group averages for selected aerobic measures during upright step test. Measures that showed a significant effect with week ($p<0.05$) are indicated with an asterisk.

<table>
<thead>
<tr>
<th>Measure</th>
<th>0 weeks</th>
<th>0 to 4 week % change</th>
<th>4 weeks</th>
<th>4 to 8 week % change</th>
<th>8 weeks</th>
<th>0 to 8 week % change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiration rate at constant cadence (breaths/min)</td>
<td>26.28</td>
<td>-7.50</td>
<td>24.30</td>
<td>-1.48</td>
<td>23.95</td>
<td>-8.87</td>
</tr>
<tr>
<td>Minute ventilation at constant cadence (L/min)</td>
<td>27.50</td>
<td>-10.21</td>
<td>24.69</td>
<td>-2.87</td>
<td>23.98</td>
<td>-12.79</td>
</tr>
<tr>
<td>$\dot{V}_{O_2}$ at constant cadence (mL/min)</td>
<td>1055.04</td>
<td>-11.634</td>
<td>932.30</td>
<td>-11.54</td>
<td>824.75</td>
<td>-21.83</td>
</tr>
<tr>
<td>Cadence at constant heart rate exercise (steps/min)</td>
<td>124.65</td>
<td>-3.45</td>
<td>120.35</td>
<td>25.28*</td>
<td>150.77</td>
<td>20.96</td>
</tr>
<tr>
<td>Maximum number of steps in 2 minutes</td>
<td>291.88</td>
<td>16.96</td>
<td>341.38</td>
<td>20.29*</td>
<td>410.63</td>
<td>40.69*</td>
</tr>
<tr>
<td>Heart rate, last 30 seconds of maximum step test (beats/min)</td>
<td>141.52</td>
<td>7.71</td>
<td>152.43</td>
<td>7.42</td>
<td>163.74</td>
<td>15.70*</td>
</tr>
<tr>
<td>Minute ventilation, last 30 seconds of maximum step test (L/min)</td>
<td>61.55</td>
<td>6.95</td>
<td>65.82</td>
<td>11.82</td>
<td>73.61</td>
<td>19.59*</td>
</tr>
<tr>
<td>Slope, heart rate vs. $\dot{V}_{O_2}$, during graded treadmill test (n=5)</td>
<td>0.034</td>
<td>-14.71</td>
<td>0.029</td>
<td>-6.90</td>
<td>0.027</td>
<td>-20.59</td>
</tr>
</tbody>
</table>
Figure 32. Cadence (steps/min) increased significantly between weeks four and eight of exercise, during an upright stepping test in which heart rate was held constant.

Figure 33. The number of steps the subject was able to do in two minutes of an upright stepping test increased significantly over the eight weeks of exercise.
Figure 34. The heart rate (beats/min) during the last 30 seconds of a maximum stepping test increased significantly over the eight weeks.

Figure 35. Minute ventilation (mL/min) during the last 30 s of the maximum step test increased significantly after eight weeks.
**Subject 10 Heart Rate vs. VO2 progression**

<table>
<thead>
<tr>
<th>VO2 (mL/min)</th>
<th>Heart rate (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>170</td>
</tr>
<tr>
<td>110</td>
<td>160</td>
</tr>
<tr>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>160</td>
<td>110</td>
</tr>
<tr>
<td>170</td>
<td>100</td>
</tr>
<tr>
<td>180</td>
<td>90</td>
</tr>
<tr>
<td>200</td>
<td>80</td>
</tr>
<tr>
<td>250</td>
<td>70</td>
</tr>
<tr>
<td>300</td>
<td>60</td>
</tr>
<tr>
<td>350</td>
<td>50</td>
</tr>
</tbody>
</table>

Regression equations are (clockwise from left): Week 0, Week 4, and Week 8.

Figure 36. Example heart rate vs. $\dot{V}_{\text{O}_2}$ data from one subject. Both heart rate and $\dot{V}_{\text{O}_2}$ increased as the grade of the treadmill was increased over the ~13-15 minute test. The slope decreases after eight weeks, and the change is more evident between weeks 0 and 4 (at eight weeks, the entire curve is shifted towards higher $\dot{V}_{\text{O}_2}$ values). Regression equations are (clockwise from left): Week 0, Week 4, and Week 8.

### 4.3.3 Strength changes

Two tests targeted strength changes, specifically. The push-ups endurance test yielded significant increases over the eight week exercise program. Six of eight subjects increased the force they were able to exert in a maximum quadriceps extension test, but over all subjects the differences were not significant. See Table 8.
Table 8. Selected strength measures. Measures that showed a significant effect with week (p<0.05) are indicated with an asterisk.

<table>
<thead>
<tr>
<th></th>
<th>0 weeks</th>
<th>0 to 4 week % change</th>
<th>4 weeks</th>
<th>4 to 8 week % change</th>
<th>8 weeks</th>
<th>0 to 8 week % change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of push-ups</td>
<td>22.5</td>
<td>11.1*</td>
<td>25.0</td>
<td>2.5</td>
<td>25.6</td>
<td>13.9*</td>
</tr>
<tr>
<td>Quadriceps extension force: all 8 subjects (N)</td>
<td>558.28</td>
<td>2.78</td>
<td>573.82</td>
<td>9.87</td>
<td>630.48</td>
<td>12.93</td>
</tr>
<tr>
<td>Quadriceps extension force: 6 of 8 subjects who increased (N)</td>
<td>525.48</td>
<td>13.54</td>
<td>596.62</td>
<td>9.16</td>
<td>651.24</td>
<td>23.93</td>
</tr>
</tbody>
</table>

Figure 37. Number of push-ups the subject could do during an endurance test increased significantly at four and eight weeks.
4.3.4 Body composition

Body composition was measured in three ways: limb circumferences (in-lab measurement sessions and CRC sessions), skinfold measurements (CRC sessions and Z-center fitness assessments), and a DXA scan (CRC session). In terms of lean vs. fat body content, we found marginally significant decreases in body fat measured in the legs (Figure 38). There was a slight decrease in leg circumference as measured in the in-lab measurement sessions at locations 1/3 and 2/3 of the distances from the ankle to the top of the tibia (this would be expected if the subject previously had excess fat in his legs). We found an overall decrease in percent body fat as measured by DXA, although this was not significant.

Data from the DXA scan also indicated an insignificant increase in total lumbar cross-sectional area (measurements from L1-L4), and a significant increase in bone mineral content of the pelvis (Figure 39). See Table 9.
Table 9. Selected measures of body composition. Measures that showed a significant effect with week (p<0.05) are indicated with an asterisk. For measures whose units are percent (e.g. percent fat), % difference is simply the difference between the two measurement sessions indicated (rather than a scaled difference).

<table>
<thead>
<tr>
<th>Measure</th>
<th>0 week</th>
<th>0 to 4 week % difference</th>
<th>4 weeks</th>
<th>4 to 8 week % difference</th>
<th>8 weeks</th>
<th>0 to 8 weeks % difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left leg percent fat (DXA)</td>
<td>23.74</td>
<td>-0.65</td>
<td>23.09</td>
<td>-0.30</td>
<td>22.79</td>
<td>-0.95</td>
</tr>
<tr>
<td>Right leg percent fat (DXA)</td>
<td>25.15</td>
<td>-1.11*</td>
<td>24.04</td>
<td>0.04</td>
<td>24.08</td>
<td>-1.08*</td>
</tr>
<tr>
<td>Left circumference (soleus)</td>
<td>28.31</td>
<td>-0.66</td>
<td>28.13</td>
<td>-0.62</td>
<td>27.95</td>
<td>-1.28</td>
</tr>
<tr>
<td>Right circumference (soleus)</td>
<td>28.50</td>
<td>-0.26</td>
<td>28.43</td>
<td>-0.88</td>
<td>28.18</td>
<td>-1.14</td>
</tr>
<tr>
<td>Left circumference (gastrocnemius)</td>
<td>38.81</td>
<td>-0.03</td>
<td>38.80</td>
<td>-0.26</td>
<td>38.70</td>
<td>-0.29</td>
</tr>
<tr>
<td>Right circumference (gastrocnemius)</td>
<td>38.94</td>
<td>-0.23</td>
<td>38.85</td>
<td>-0.45</td>
<td>38.68</td>
<td>-0.68</td>
</tr>
<tr>
<td>Total body percent fat (DXA)</td>
<td>23.00</td>
<td>-0.55</td>
<td>22.45</td>
<td>-0.18</td>
<td>22.28</td>
<td>-0.73</td>
</tr>
<tr>
<td>Total lumbar area (cm^2)</td>
<td>64.15</td>
<td>0.23</td>
<td>64.29</td>
<td>0.48</td>
<td>64.60</td>
<td>0.71</td>
</tr>
<tr>
<td>Bone mineral content, pelvis (g)</td>
<td>289.97</td>
<td>-0.72</td>
<td>287.87</td>
<td>2.89*</td>
<td>296.19</td>
<td>2.15</td>
</tr>
</tbody>
</table>
Figure 38. Significant or marginally significant decreases in percent fat of the legs were seen after four or eight weeks of exercise, as measured by DXA scan.

Figure 39. Significant increase of pelvic bone mineral content (g) between weeks 0 and 8. Not all subjects showed increases.
4.3.5 Other effects and non-effects

There were no significant changes in the response to the Romberg balance test, nor were there changes in the response to the orthostatic stand test. Body weight did not change significantly (an average decrease over eight weeks of 0.01 kg). Subjects did experience an insignificant increase in flexibility in the sit-and-reach test, on average 9.4 cm (3.7 inches) after eight weeks.

4.3.6 Exit surveys

Eight out of nine subjects said that exercising in the dark did not feel unnatural; the ninth said that it stopped bothering him after three to four sessions. Four of the subjects reported some initial pain or stiffness for the first few sessions, including lower back pain (two subjects), neck stiffness (two subjects), and shoulder pain (one subject). Five subjects reported that they felt sore muscles when they began the exercise program (legs and arms). Two subjects disliked the repetitiveness of the arm exercise, and two others mentioned discomfort due to sweat collection beneath their back. When asked the best part of exercising on a centrifuge, three subjects reported that they simply enjoyed being on a centrifuge and/or the slight tumbling sensations during minor head movements, and four subjects said that they enjoyed watching movies while they were exercising.

None of the nine subjects felt motion sick while exercising on the centrifuge, except when they moved their heads. One subject did feel motion sick in the hours following his exercise sessions, which led to his eventual discontinuation of the program. Six of the nine subjects reported that they effectively forgot that they were spinning; for most subjects this happened as early as the first session. They also reported that the feeling of spinning disappeared almost immediately when the centrifuge began spinning – for three subjects, before the centrifuge was even at full speed. Two subjects felt that the exercise sessions were probably too short to improve their fitness, two felt that they were too long (including the dropout subject), and five felt that the length of the sessions was appropriate. Three subjects commented that they believe the target heart rates should have been higher. All subjects said that stair-stepping was a good type of exercise given the constraints of the centrifuge, but several of them commented that they wished for more range of motion. Two subjects suggested using a cycle ergometer for variety, and two subjects suggested more of a variety of arm exercise capabilities as well. All
subjects felt that the stretching they did (which was not monitored explicitly by the experimenter) was sufficient. The subjects reported that they had no trouble watching a movie while spinning, even with subtitles (one subject), although if part of the movie was very quiet, they sometimes had trouble hearing it through their headphones. The change of direction every day did not bother any of the subjects; in fact, five of the subjects reported that they did not notice the change in direction every other day. All but one subject noticed the Coriolis accelerations with various movements: six noticed the feeling in their arms, three noticed it in their legs or knees, and one subject felt the lateral movement in his hips. Some subjects stopped noticing the feeling, others did not. For the arm exercise, all nine subjects did primarily biceps curls, with some subjects periodically switching to forward flyes or upward rows.

Subjects had some suggestions for improvement: availability of water while exercising on the centrifuge, adjustable resistance and range of motion for the stepper and for the arm exercisers, a mesh or absorbent pad beneath the back, a more reliable heart rate monitor, constraints against out-of-plane motion (to reduce Coriolis accelerations), and an integrated heart rate display on the movie screen. None of these changes were made to the protocol during this experiment.
Chapter Five

Discussion

In these two experiments we have investigated artificial gravity and exercise as a countermeasure to spaceflight physiological deconditioning: first in terms of the practical issues of centrifuge radius and short-term physiological responses, then with respect to its effectiveness in improving fitness.

The purpose of this chapter is to review the findings of Chapters Three and Four. In Chapter Three, we found that exercise on a centrifuge attenuates the physiological responses to high g-levels and high g-gradient centrifugation (Section 5.1, below). In Chapter Four, we found that subjects were able to successfully and comfortably exercise on the centrifuge for long periods of time over an eight week exercise program, with no negative side effects; we also began to see indications of fitness improvements (Section 5.2).

5.1 Experiment 1: The effect of light exercise on the physiological response to a gravity gradient

Hypothesis 1.A. Heart rate and blood pressure will both increase as a result of increasing g-level. Heart rate will increase and blood pressure will decrease with decreasing tilt angles.

Hypothesis 1.B. Calf volume will increase with increasing g-levels and decreasing tilt angles. Right calf volume will be lower when standing on both feet than when allowing the
right leg to relax and hang freely. Calf volume will be lowest, on average, when stepping in place.

Hypothesis 1.C. Stepping in place will reduce the heart rate and blood pressure responses to changing g-level and g-gradient.

5.1.1 Heart rate and blood pressure responses

As expected (Hypothesis 1.A), heart rate increased as g-level increased, and as g-gradient increased (tilt angle decreased). The regression line shifted up (generally higher values) for higher g-gradients, and shifted down (generally lower values) for lower g-gradients. The heart rate increase was due to the need for an increase in cardiac output, a response to the decrease in venous return with increasing g-levels. Blood pressure also increased with increasing g-levels, as expected: this increase was due to the fact that, in order to maintain nominal pressure at the level of the carotid baroreceptors, the pressure at the heart increased as described in Equation 3. However, we saw an unexpected effect on blood pressure for tilt. Blood pressure increased with decreasing tilt angles. On the ESA centrifuge, lower tilt angles place the subject’s head closer to the center of rotation, so the pressure difference between the heart and the carotid baroreceptors is less for these low tilt angles due to the fact that the net g-level acting on this neck-to-heart segment is greater for higher tilt angles. This is illustrated in Figure 40: for any given g-level at the heart, the g-level at the head is higher for higher tilt angles. As a result, the total pressure from the neck to the heart is greater for higher tilt angles. Thus, we would have expected a greater blood pressure compensatory response for higher tilt angles, but we saw the opposite response. This may have been simply a sympathetic stress response. As g-level at the feet increased (the lower tilt angle conditions), the subject became anxious or tensed his muscles, increasing blood pressure.
Figure 40. G-levels for the head, heart, and feet during Experiment 1. Each color represents a different g-level at the heart (0.7, 1.0, 1.2, or 1.4), and each color has three lines to represent three tilt angles: $0^\circ$ is always the highest g-level at the feet (diamond symbols), $21^\circ$ is the middle tilt angle (square symbols), and $45^\circ$ gives the lowest g-level at the feet (triangle symbols). Although $0^\circ$ gives the highest g-level at the feet, it also gives the lowest g-level at the head. Thus, although the head-to-heart g-gradient is greater for lower tilt angles, the average head-to-heart g-level is less for lower tilt angles.

It is useful to check that the blood pressure changes that we saw due to changing g-level were approximately what we would expect based on the pressure differential between the heart and the carotid baroreceptors (Equation 3 and Figure 20 from Chapter Three). If the distance between the heart and carotid baroreceptor is assumed to be 25 mm, then the static hydrostatic pressure equation ($\Delta P = \rho g \Delta h$) tells us that 1.0-g would result in a difference of 27 mmHg between the head and neck. In our experiment, we found changes of between 12 and 26 mmHg per g-level based on Table 5; thus, the increasing arterial blood pressure that we saw with increasing g-level was on the order of what we should expect based on the pressure difference between the heart and carotid baroreceptors.

5.1.2 Right calf volume responses

We found that right calf volume increased the most (3.5% increase per g-level on average) when the leg was relaxed (Hypothesis 1.B). The effect of g-level was reduced when standing on both feet. Evidently even the low-level muscular activation of standing on both feet helped to promote venous return and maintain the volume of the calves. Stepping in place
further decreased the calf volume, due to the venous pump [39]. The response to this volume increase in the legs and the resulting orthostatic challenge was an increase in heart rate and blood pressure with increasing g-levels, as explained above. Without such an appropriate compensatory response, we would have seen decreased arterial blood pressure measured in the upper half of the body, due to the drop in blood volume in the upper body. This has certainly been seen in past studies: decreased blood flow at the level of the head at 100% gradient, as measured by an earlobe pulsogram, as been shown for g-levels of 0.8- to 1.6-g (no specification of where this was measured) [145]. We would have expected significantly higher calf volumes for lower tilt angles, due to the fact that g-level is higher at the level of the calves for lower tilt angles. This effect is apparent in Figure 17, but not significant.

The slight drop in calf volume at the high g-levels is probably due to the fact that only three subjects (two shown here) were spun to the level of 1.4-g at the heart; it may also have been a result of strain gauge slippage on one or more subjects.

5.1.3 The effect of stepping in place

Stepping in place mitigated the increase in heart rate with respect to g-level and g-gradient (Hypothesis 1.C). Although the effect of g-level was still significant for all three actions (one foot, two feet, and stepping in place), the heart rate response was significantly less (12.7 beats/min increase per g-level, as opposed to 26.9 or 30.5 beats/min.) Heart rate increased as g-level increased in order to increase cardiac output and respond to the orthostatic challenge; however, stepping in place aided in venous return, such that the orthostatic challenge was decreased. Specifically, repetitive muscular contractions and relaxations in the lower legs help to return blood to the upper half of the body. This has been shown to be true in normal standing and walking ([118], see Background, Figure 9); additionally, previous studies have shown that tolerance to high g-levels on a centrifuge increases (g-level and time spent on the centrifuge) when the subject is exercising [108]. Stepping in place also completely removed the significant effect of changing g-gradient.

Unlike calf volume and heart rate, stepping in place increased the arterial blood pressure at heart level. This may be because the venous pumping mechanism, as described above, helps to return blood to heart level – thus, pressure at heart level would increase, rather than decrease. It may also be due to the general exercise effect of increasing blood pressure.
5.1.4 Off-axis accelerations

In our study we have concentrated on the vector sum of Earth’s gravity and artificial gravity along the body axis ($G_z$). However, the total sum of these two vectors (“gravito-inertial acceleration”, or GIA) is usually not exactly parallel to the body axis. In fact, the GIA sometimes differs by as much as 50° from the body axis, depending on where it is measured (direction is always positive out the back, and is measured as 0° if it is aligned from the head to the feet). Usually the GIA is directed out the subject’s back, but in the most extreme case (45° tilt angle, spun to 1.4-$G_z$ at the heart), the 1.9-g magnitude GIA is directed 14° forward, at the location of the subject’s head (at his feet, the 1.2-g magnitude GIA is directed 12° behind the subject) – see Figure 41. It does not seem probable that the GIA direction affects the physiological results. In the case described above, the GIA vector is only 14° forward from the subject’s front: the component of this vector perpendicular to the subject’s body is less than 0.5-g. For the greater, 50° GIA angle, the magnitude is only 1.3-g, and it is towards the subject’s back. This is less than we experience when lying supine and not spinning (1-g at an angle of 90°).
5.1.5 Short- vs. large-radius centrifugation

As presented in the introduction, the tilting design of the SAHC allows the emulation of the effects of increasing or decreasing the radius of a non-tilting centrifuge (such as a space
This, of course, neglects the effect of accelerations out of the plane of the body; see discussion above. To illustrate this, average g-level and rotation rates for subjects of this experiment are given in Table 10. We also show the necessary radius and rotation rate of a space centrifuge – essentially, what characteristics of a space-based centrifuge would be required to match our tilt stimulus in terms of g-level and g-gradient. For the space centrifuge we give values for an example subject of 1.78 m, the average height value of our subjects. Figure 42 gives “iso-gradient” lines for several g-gradients, illustrating that the same g-gradient can be achieved by a tilting centrifuge or a varying radius centrifuge.

Table 10. Average g-levels and rotation rates (± standard deviation) for all subjects. For 21° and 45° tilt, the radius and rotations per minute (RPM) required to achieve the same g-gradient on a non-tilting space-based centrifuge are also given (“radius space” and “RPM space”). Highlighted numbers, see text.

<table>
<thead>
<tr>
<th>g-level at heart</th>
<th>0 degrees tilt</th>
<th>21 degrees tilt</th>
<th>45 degrees tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>g-level, head</td>
<td>g-level, feet</td>
<td>RPM</td>
<td>g-level, head</td>
</tr>
<tr>
<td>0.70</td>
<td>0.40 ± 0.01</td>
<td>1.73 ± 0.02</td>
<td>26.62 ± 0.20</td>
</tr>
<tr>
<td>1.00</td>
<td>0.58 ± 0.01</td>
<td>2.47 ± 0.03</td>
<td>31.84 ± 0.22</td>
</tr>
<tr>
<td>1.20</td>
<td>0.69 ± 0.01</td>
<td>2.97 ± 0.04</td>
<td>34.83 ± 0.26</td>
</tr>
<tr>
<td>1.40</td>
<td>0.82 ± 0.01</td>
<td>3.43 ± 0.03</td>
<td>37.83 ± 0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>g-level at heart</th>
<th>g-level, head</th>
<th>g-level, feet</th>
<th>RPM with tilt</th>
<th>radius space (m)</th>
<th>RPM space</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>0.71 ± 0.00</td>
<td>0.71 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>infinite</td>
<td>n/a</td>
</tr>
<tr>
<td>1.00</td>
<td>0.93 ± 0.00</td>
<td>1.23 ± 0.01</td>
<td>17.84 ± 0.08</td>
<td>7.12</td>
<td>12.41</td>
</tr>
<tr>
<td>1.20</td>
<td>1.09 ± 0.00</td>
<td>1.59 ± 0.01</td>
<td>23.14 ± 0.10</td>
<td>5.44</td>
<td>16.13</td>
</tr>
<tr>
<td>1.40</td>
<td>1.25 ± 0.00</td>
<td>1.94 ± 0.01</td>
<td>27.53 ± 0.06</td>
<td>4.81</td>
<td>18.95</td>
</tr>
</tbody>
</table>
Figure 42. “Iso-gradient”, for different configurations in which the subject is spun to 1-g at the heart (note that rotation rate is varied as needed within this plot to achieve the desired gradient). For example, it is possible to achieve a 20% gradient on a non-tilting, nearly 10m centrifuge; it is also possible to achieve a 20% gradient on the ESA (2.2m) centrifuge when tilted to an angle of nearly 50 degrees.

We may draw some conclusions about how the centrifuge orthostatic response compares with Earth-upright. We see from the results of this experiment that, when spun to a 1.0-g level at the heart (for example), the 0° and 21° tilt angles induce a higher heart rate than the 45° tilt angle. To translate this to a space centrifuge, that means an approximately 2-3 m centrifuge (similar to the 0° and 21° tilt conditions) produces a response more stressful than upright (if spun at an RPM such as to induce 1 g at the level of the heart), but an approximately 7 m centrifuge (simulated by the 45° tilt angle) is fairly similar to Earth-upright. See highlighted text in Table 10.
5.1.6 Summary

The results of this experiment suggest that a short-radius centrifuge would be more stressful (e.g. higher heart rate and blood pressure) than a larger-radius centrifuge (simulated here with tilt angles up to 45°). In particular, standing on one foot or two feet on a short-radius centrifuge resulted in increasing calf volumes, heart rates, and blood pressures for increasing g-levels; however, this effect was seen to a lesser extent for higher tilt angles (simulating larger radii). When exercising, the short- vs. large-radius differences were considerably mitigated. For example, within the limits of our study, exercise completely removed the significance of the g-gradient, indicating that the radius of the centrifuge does not matter as long as the subject is exercising (again, within the limits of our study). If exercise is always used on the centrifuge, then, it may be unnecessary to use a large-radius centrifuge. At the very least, exercise can be used to mitigate orthostatic responses to high g-level stimuli on a centrifuge.

5.2 Experiment 2: Effectiveness of stair-stepping during centrifugation

Hypothesis 2.A. Subjects will be able to complete eight weeks, three times per week of exercise (20-40 minutes duration) using a stair-stepper on a short-radius centrifuge, with little or no discomfort.

Hypothesis 2.B. Aerobic fitness will improve as a result of eight weeks of stair-stepping exercise on a centrifuge.

Hypothesis 2.C. Quadriceps strength and push-ups endurance will improve as a result of eight weeks of stair-stepping and arm exercise on a centrifuge.

Hypothesis 2.D. Body composition will improve (decreased body fat percentage, increased bone mineral content) as a result of eight weeks of stair-stepping on a centrifuge.

Hypothesis 2.E. Neither balance nor orthostatic tolerance will change as a result of an eight week exercise program of stair-stepping on a centrifuge.

5.2.1 Effectiveness of exercise sessions

Eight out of nine subjects were able to complete an eight week exercise program on the centrifuge (Hypothesis 2.A), and we find minor fitness improvements in these
subjects, with some significant changes. Significant changes are summarized in Tables 7-9 (Chapter Four). Briefly, we found a significant increase in upright stepping cadence at a given heart rate; a significant increase in the maximum number of steps done during a 2-minute upright stepping test, as well as a significant increase in heart rate and minute ventilation achieved during this upright test; a significant increase in the number of push-ups the subject was able to do; a significant decrease in percent fat in the right leg; and a significant increase in the bone mineral content of the pelvis. The small number of significant changes is likely due to (1) high variability in testing, even within subjects, and (2) a short exercise period. The high variability is probably due to several uncontrolled factors. Generally, diet was uncontrolled, as was general activity level. Although subjects were not permitted to take part in any exercise program outside of this study, their level of daily activity was not monitored: for example, walking to and from class, and weekend excursions. Test conditions were controlled as closely as possible, but certain requirements were beyond our control, including how much the subject had slept the night before, and his general motivation that day. In terms of the length of the study, a discussion below will outline results from existing literature, highlighting the time course of effects.

The subject who terminated the exercise program after four weeks due to headaches between sessions was probably not sufficiently evaluated prior to his selection for the study. Unlike the other subjects, he did not enjoy being on the centrifuge, and strongly disliked exercising beyond 20 minutes.

Some unusual artifacts of artificial gravity exercise should be noted. One subject reported that exercising in the dark felt somewhat unnatural; however, he became accustomed to it after 3-4 sessions. Some subjects also subjectively reported that increasing their heart rate to the target level was more difficult on the centrifuge than it was when stepping upright. This was probably due to the fact that, although they were in an artificial gravity environment, they were still lying down, resulting in a higher stroke volume [146] but, presumably, a lower base heart rate. This does not necessarily confound our study, since heart rate may be lower in microgravity than it is on Earth [27]. Although it was not explicitly recorded here, a simple experiment could be used to test this subjective report: compare heart rate levels at certain Borg ratings of perceived
exertion, both upright and when exercising on the centrifuge. Practically, using the resistive arm bands helped subjects to increase their heart rate when on the centrifuge. Our observations of heart rate during the sessions also indicated that target heart rate can only be used loosely in exercise prescription [138]; the trainer must be attentive to individual differences. We deviated significantly from the generalized heart rate assignments in order to maintain the desired rating of perceived exertion. For example, sessions 4, 5, and 6 were loosely designated 45% HRR sessions. One subject reported a rating of “somewhat hard” during these sessions, and so the experimenter asked him to maintain this heart rate value for the next exercise session. Another subject, by session 4, was exercising at a target heart rate of 55% HRR, due to earlier ratings of “fairly light” at lower target heart rates.

The absence of some effects should also be discussed. During sessions and throughout all sessions, subjects reported no knee or hip pain due to Coriolis accelerations. This may or may not be due to spinning the centrifuge in alternate directions on alternate days, and this negative finding is in agreement with previous studies [147]. Subjects did not experience diminished balance as measured by the Sharpened Romberg test (Hypothesis 2.E). Although a gross measure of balance, we may be reasonably assured that stair-stepping on a centrifuge three times per week does not seriously impair the subject’s balance in a non-spinning Earth-gravity environment, nor does it impair his normal 1-g locomotion. In the worst case, we might have found that exercise while rotating would have a negative effect on non-rotating posture and balance. Orthostatic tolerance, as measured by steady-state heart rate and blood pressure responses to supine, sitting, and standing body positions, also did not change over the eight week exercise program (Hypothesis 2.E). We certainly did not expect to see changes; there is only minimal evidence of any differences between athletes and non-athletes in terms of orthostatic responses [61, 63, 64], and would probably require considerably more than eight weeks of training to show such effects in any case. Nevertheless, we are encouraged that a centrifuge exercise program does not change the subject’s responses to orthostatic stress.
5.2.2 *Variability in fitness responses*

It is known that fitness responses to exercise vary widely among individuals, even if the stimuli are identical. In one study, identical training protocols resulted in \( \dot{V}_{O_2} \)-max changes of between 0 and 58% between subjects, and the only consistent predictor of exercise response was familial relations (heredity), whereas age, sex, and race had almost no effect, and pre-exercise fitness levels had a trivial effect [148]. After a 20-week training program in another study, heart rate at a constant work rate decreased by an average of 11 beats/min, but the standard deviation was as high as 10 beats/min; in this case, baseline levels, sex, and familial relations were the strongest predictors [149]. Baseline levels were also an important predictor for systolic blood pressure changes at a constant work rate. For a review of these studies, see [150]. The American College of Sports Medicine recommends exercise 3-5 days per week at a 40 or 50% to 85% HRR (the lower value, 40%, used for sedentary subjects just beginning exercise). It is suggested that each exercise session last 20-60 minutes, with duration adjusted inversely with intensity [143]. For our study, the lower limits of these guidelines were followed: exercise ranged from 40-55% HRR, took place 3 days/week, and lasted 20-40 minutes.

5.2.3 *Comparison with upright stepping*

Because we were not able to enroll an upright stair-stepping group as well, we will attempt to compare our results with results from existing literature in which upright exercise was used as a stimulus for improving fitness. This is not nearly as useful as having a control group, but allows for some context when postulating how much improvement we should have expected to see in eight weeks.

5.2.3.1 *Exercise specificity*

When looking specifically at aerobic capacity over the eight weeks of exercise, we saw marginal improvements (*Hypothesis 2.B*). Several improvements were seen in the upright stepping test, with lesser improvements seen in the treadmill \( \dot{V}_{O_2} \)-max test. This may indicate that performance was highly specific to the mode of exercise; that is,
testing on a stair-stepper yielded the most obvious results, since the subject trained on a stair-stepper. The phenomenon of exercise specificity has been seen previously [132]. In a fourteen day bedrest study [80], twelve men acted as controls (no countermeasure), or performed five sets of leg presses to fatigue, every other day. After the bedrest period, subjects were tested for leg strength using a different exercise device, an isokinetic knee extension machine. The results showed that there were no differences between the countermeasure and no countermeasure group. The authors attribute this negative result to the several differences between the training exercise and the testing exercise, including using an isokinetic (constant velocity knee extension) mode of exercise for testing rather than the constant load (leg press) mode of exercise used for training, and the fact that training was bilateral (both legs) and testing was unilateral (one leg). In another study in which subjects exercised using a cycle ergometer with either their arms or their legs, subjects were tested after the four-week training program, using both modes of exercise. Those who exercised with their arms exhibited markedly lower heart rates for a given work rate, for arms but not legs. Those who exercised with their legs exhibited significantly lower heart rates for a given work rate for their legs but not arms. These authors suggest that heart rate may decrease for that specific mode of exercise due to training of the specific skeletal muscles used during testing, which may reduce the autonomic response (in this case, increasing heart rate) that was previously required during use of those muscles [151].

5.2.3.2 Recovery

After the upright stepping test, we expected to see quicker rate of recovery (heart rate, oxygen consumption) in subjects after eight weeks of training. In a four-week study, non-athletic subjects participated in a 30-minute cross-country running program five days per week (increasing to 90-minutes per day by the last week). After this training period, they experienced lesser heart rate values and quicker heart rate recovery for a given standard treadmill rate of 4 mph at a grade of 10% [152].
ExerCise Protocols during short-radius centrifugation for artificial gravity

Figure 43. Elsner and Carlson [152] found significant improvements in recovery after training for non-athletes; this figure shows the mean heart rate of non-athletes in standard treadmill exercise before and after training. Differences are significant (p<0.001).

It is likely that the reason we did not see this was that the pre-recovery stimulus varied. In our upright step-testing, subjects warmed up for three minutes, stepped at a constant cadence for three minutes, stepped at a constant heart rate for three minutes, then finally, stepped as fast as possible for two minutes. Recovery followed this maximal stepping portion, during which subjects significantly increased their cadence of stepping, as seen in Section 4.3.2. This is why we also saw increased heart rate and minute ventilation after one and two minutes, rather than seeing decreases in these parameters. Indeed, previous studies have shown that after only 20 minutes of exercise at a level of 70% \( \dot{V}_{O_2} \)-max, resting oxygen uptake can be elevated for as much as 12 hours [153].

5.2.3.3 \( \dot{V}_{O_2} \)-max treadmill test

Studies as short as four weeks have shown changes in \( \dot{V}_{O_2} \)-max ([154], discussed below). We saw neither changes in \( \dot{V}_{O_2} \)-max as extrapolated from treadmill data, nor significant changes in the slope of heart rate vs \( \dot{V}_{O_2} \); however, slope did decrease, on average, for the five subjects with data that could be reasonably fit to a line (Figure 36). We expected to see a change in the slope: individuals with better aerobic fitness levels will have a higher oxygen uptake for a given heart rate, at high levels of exertion [124].
A study of twelve sedentary men versus fourteen successful athletes revealed an average maximal oxygen uptake of 4.8 L/min (71 mL/min/kg) for the athletes versus 3.2 L/min (44 mL/min/kg) for the sedentary men. For women, five athletes averaged 3.3 L/min (55 mL/min/kg) and twelve sedentary women averaged 2.3 L/min (38 mL/min/kg) [135]. Observations from this study led to the hypothesis that both slope and intercept of the heart rate/$\dot{V}_{O_2}$ relation should decrease with increasing fitness. We find that our values match closely with those for non-athletes from the data above (also presented in Figure 44), although changes over the eight weeks are difficult to discern visually. Interestingly, data from Apollo 7-11 astronauts showed a significant increase in the heart rate/$\dot{V}_{O_2}$ relation during a graded stress test on the first day postflight; the authors attributed this primarily to decrease stroke volume [41].

![Figure 44. Heart rate (beats/min) vs. $\dot{V}_{O_2}$ (L/min), our data (red) overlayed with data from Hermansen and Andersen [135]. Hermansen and Andersen data was taken during a cycling test of increasing difficulty, and two or three data points per subject are shown as the subject increased from submaximal to maximal work loads. For our data, not all data points from all subjects are shown (this would completely obscure the background data); rather, average $\dot{V}_{O_2}$ values corresponding to approximately 10 selected heart rate values per subject are shown. Data from our experiment matches the Hermansen and Andersen data well for non-athletes, but tends towards athletes by week 8.](image-url)
5.2.3.4 Exercise intensity and duration

It must be suggested the subjects may not have exercised at a high enough level of exertion to produce measurable results after eight weeks. A Borg rating of 13-15 was used to establish target heart rates, in an attempt to downplay variations in heart rate responses between individuals. Subjective ratings, though, have their own faults: in a meta-analysis of correlations of the Borg rating with objective measures, investigators found that the Borg rating may not correlate as highly with physiological measures as previously thought ($r=0.80-0.90$), particularly with very homogeneous groups. They noted that the Borg RPE tends to work best at high exertion levels, or when the type of exercise is unusual [155]. We may also have seen a repetition effect – subjects who usually reported 13 may have continued to report 13, because they did not detect any change in the exercise difficulty from session to session.

We should also consider if eight weeks was long enough to see aerobic changes. Luasen et al [151] and Elsner and Carlson [152] saw decreases in heart rate for a given work rate after 8- and 4-week exercise programs, respectively, described above. In another study, ten healthy untrained men exercised for eight weeks, 1 hour/day on a cycle ergometer at 70% HR$_{max}$ (~50% HRR) [156]. These subjects were tested at a constant work rate at 0, 4, and 8 weeks: heart rate was measured during this exercise test and for three minutes post-exercise. Heart rate was significantly lower during exercise, and the time required to return to the heart rate level achieved after 30s during week zero was significantly reduced after four and eight weeks. In our study, we also saw higher work rate for a given heart rate, which is similar to the above studies, which were of the same or lesser duration. We did not see faster recovery (see explanation above). Thus, in this respect, eight weeks appear to have been long enough. However, we did not find significant changes in $\dot{V}_O_2$-max, which have been measured in studies less than eight weeks ([154], see below). These mixed results suggest that a longer exercise protocol should be used in future studies, in order to see more significant changes in more fitness measures.

We measured resting parameters in our subjects: heart rate and blood pressure, and resting energy expenditure. While a year-long study with healthy marathon trainees [60], and a 10-week study with sedentary and hypertensive subjects [157], showed
evidence of reduced resting cardiovascular parameters, we did not see resting changes in these subjects. This is mostly likely due to the fact that the exercise program was too short to measure changes in resting parameters, and also the fact that, although our subjects were sedentary, they were otherwise healthy.

A study of 8 subjects (4 women, all with $\dot{V}_{O_2}$-max less than 45 mL/min/kg) during a diet-and exercise program revealed changes in muscle growth and aerobic capacity [154]. Subjects’ diets were controlled for six weeks, and for the last four weeks, they exercised 3-5 times per week for 30-45 minutes, at greater than or equal to 65% maximum heart rate (~42% HRR). While there was no change in body mass or composition, there was a change in skeletal muscle protein turnover (as measured by blood samples muscle biopsies from the vastus lateralis). Resting energy expenditure and $\dot{V}_{O_2}$-max both increased significantly, and there were significant decreases in running time during a timed trial. Comparing this with our study, our subjects exercise at similar heart rate levels, but we did not see changes in resting energy expenditure or $\dot{V}_{O_2}$-max. This may be partially because our subjects’ diets were not controlled. However, we did begin to see changes in leg strength and body composition (*Hypotheses 2.C and 2.D*), which are related to increases in skeletal muscle protein turnover. We also saw significant increases in a timed stair-stepping test, which may be likened to the running time trial in the study outlined above. It is interesting that in our subjects, push-ups endurance increased significantly, while maximum leg force did not. Since arm exercise was not controlled, it appears that the generic improvement in upper body strength was sufficient to improve push-ups endurance.

The above review leads us to conclude that eight weeks were required to see even modest fitness gains. Specifically, we saw some improvements in body composition, strength, and aerobic capacity (particularly for the same mode of exercise). We believe that stair-stepping on a centrifuge is approximately as effective as many types of upright exercise, in terms of fitness benefits.
5.2.4 Stair-stepping as an exercise modality

It is useful to look specifically at stair-stepping as a mode of exercise, in comparison with other modes of exercise. Previous work with cycle ergometry on a centrifuge has been discussed in Chapter Two. In addition to this mode of exercise, squats have been demonstrated to be feasible and comfortable on an artificial gravity centrifuge. For subjects on a gondola-type centrifuge (free swinging) with a cage-type enclosure, subjects were usually able to perform 10 squats at 1.5, 2.0, 2.5, and 3.0-Gz as measured at the base plate at the subjects’ feet (with the exception of some male and female subjects who were limited by their own strength and not able to perform squats at 3.0-Gz). Additionally, ground reaction forces at 3.0-Gz averaged 2.3-2.4 times those measured at 1-Gz over the squat period. Interestingly, this centrifuge was powered by another rider who cycled to provide power [114]. Experiments in our lab have indicated that mediolateral knee displacements during squats against body weight, and additional resistive load of up to 25% body weight, are in the range of 1.0-2.0 cm, and do not pose any concern in terms of biomechanical safety [147]. Peak foot forces in these experiments reached 200% body weight, in large part due to radial shift in the subject’s center of mass when he bent his knees.

Greenleaf et al [158] suggest a training protocol for astronauts that includes 30 min/day on an isotonic cycle ergometer and 10 sets of 5 repetitions on an isokinetic cycle ergometer, which, according to these authors, could maintain approximately 90% of aerobic capacity, strength, and endurance. In an Earth-based test of the Interim Resistive Exercise Device (iRED, similar to the device on the International Space Station), subjects enrolled in a 16-week training program using either this device or free weights, in similar exercise protocols. Investigators found that the iRED produced the same changes in muscle mass and strength as the free weights, but there were no changes in bone mineral density in the iRED group; BMD did, however, increase significantly in the lumbar area for the free weights group [159].

Stair-stepping on a centrifuge has the desirable quality of producing relatively high foot forces (Figure 45. Comparison of foot forces upright walking and cycling, and stair-stepping on the MIT Short-Radius Centrifuge at 30 RPM. One step or cycle for one foot is shown. Walking and cycling data from Thornton [20]. Peak impact foot forces
during our exercise sessions (up to 124% body weight) are on the order of weightless treadmill running using bungee tie-downs (~130% body weight peak impact forces, tested in parabolic flight [83]). These forces could be increased by using higher centrifuge velocities, or loading the subject further using bungees. It is likely that the reason footplate forces varied for different subjects is due to varying biomechanical strategies - it has been shown that it is possible for subjects to change the forces on their feet during centrifugation, through isometric contraction of their legs [160].

![Figure 45. Comparison of foot forces upright walking and cycling, and stair-stepping on the MIT Short-Radius Centrifuge at 30 RPM. One step or cycle for one foot is shown. Walking and cycling data from Thornton [20].](image)

The motion of stair-stepping also more closely mimics that of walking than, for example, cycling does. Locomotion training may be important during a long-duration spaceflight, particularly en route to a planetary surface where walking will be necessary during EVA; practicing the stepping/walking motion in space could arguably stimulate appropriate pathways from the motor cortex, to make walking on the surface of the moon or Mars feel more natural to the astronauts. Ideally, the exercise device would also
include a forward stroke; perhaps it would be possible to implement some type of treadmill device on the centrifuge.

5.2.5 Rehabilitation applications

Aside from the obvious spaceflight utilization of a centrifuge and exercise system, it is possible that a system such as this could be used in rehabilitation scenarios. Centrifuge exercise has successfully prevented physiological deconditioning in bedrest when used for spaceflight studies [10, 49, 109]. Therefore, it may also be prescribed for people who are confined to bedrest for other reasons, and we have shown here the relatively long-term usability of this countermeasure. Exercise other than stair-stepping could certainly be implemented on a centrifuge to cater to the specific needs of the patient. In addition to a primarily aerobic stimulus such as stair-stepping, resistive exercise (e.g. squats) should be included on a rehabilitation centrifuge in order to more precisely target muscular development. Fairly robust patients might also benefit from g-loads above 1-g to expedite recovery.

5.3 Recommendations

Based on the results from Experiment 1, it is evident that light exercise should at the very least be supported, if not required, if a centrifuge is to be considered for a spaceflight countermeasure. Depending on the subject height, g-level, and certainly centrifuge radius, the physiological responses to centrifugation may be intolerable. In our experiment, we intended to test subjects to a level of 1.4-g at the heart, and downgraded to 1.2-g at the heart after two subjects became presyncopal. If problems were seen in these healthy subjects at these levels, we must consider the consequences for deconditioned astronauts. Light exercise mitigated these effects considerably; this is an easy addition to a centrifuge to ensure the safety of its users.

Experiment 2 indicates that stair-stepping on a centrifuge is a potentially effective means of improving fitness in healthy subjects. We recommend a similar experiment using deconditioned subjects (e.g. bedrest), to test specifically if fitness can be maintained. Based on our results, we believe that stair-stepping on a centrifuge is as effective as typical upright exercise programs, and should be considered as a spaceflight
countermeasure to various physiological detriment. Additionally, these experiments certainly support the use of a stair-stepper specifically in terms of comfort and potential fitness benefits. Based on its other benefits (high foot forces and locomotion training), a stair-stepper should be considered as a centrifuge exercise device.

It would be useful to combine previous studies’ results that exercise during centrifugation is effective in preventing bedrest-induced deconditioning [10, 49, 109] and this study’s results that exercise during centrifugation may improve fitness. This could be achieved by repeating the protocol of Experiment 2 with bedrested subjects. The experiment should attempt to answer the question of whether fitness improvements can be achieved over an extended period of time, for subjects who exercise on a centrifuge during a bedrest period.

Most questions about artificial gravity and exercise during centrifugation would best be addressed using a space-based centrifuge. The most definitive way to test tolerance to short-radius centrifugation and effectiveness of exercise during centrifugation would be to test it on ISS with long-term crewmembers. This would allow us to directly measure the risks and benefits of such a system, and decide whether or not to implement it in future human Mars missions. Issues regarding energy requirements and spacecraft disturbances of a space centrifuge are addressed in detail in Appendix B.
Chapter Six

Conclusion

6.1 Summary of major findings

We set out to investigate two related hypotheses:

Hypothesis 1. Exercise during centrifugation will attenuate heart rate, blood pressure, and calf volume increases due to increasing g-levels and g-gradients.

Hypothesis 2. An exercise program consisting of stair-stepping on a centrifuge will effectively improve fitness, as measured by aerobic capacity, muscular strength and endurance, and body composition.

6.1.1 Hypothesis 1

Increasing g-level had a significant effect on heart rate, blood pressure, and calf volume, and increasing g-gradient had a significant effect of heart rate and blood pressure. Allowing the right leg to hang freely resulted in the highest calf volumes, as well as the highest heart rates. However, stepping in place mitigated the effects of g-gradient on increasing heart rate by activating the venous pump, returning blood to the upper part of the body, and removing the orthostatic stress that, when the subject was standing still, required an increase in heart rate to compensate for the decrease in venous return. When stepping in place, the effect of tilt on heart rate was no longer significant,
and the effect of g-level on heart rate was reduced (Figure 46). In short, there was less physiological response to changing g-levels and g-gradients when the subject stepped in place. This may imply that by having the subjects perform light exercise, the question of short- vs. large-radius centrifuge is no longer pertinent, at least within the g-levels that we tested.

(a) Heart rate (right leg hanging)  
(b) Heart rate (stepping in place)

Figure 46. Heart rate data when (a) allowing one leg to hang freely, and (b) stepping in place. Heart rate increases significantly with increasing g-level and g-gradient when standing on one foot, but the significant effect of tilt is removed when the subject stepped in place.

6.1.2 Hypothesis 2

We found minor fitness improvements for subjects who took part in an eight week exercise program on the stair stepper. These improvements were measured by aerobic capacity and endurance (significant (p<0.05) increase in work rate for a given heart rate, significant increase in stepping endurance (Figure 47)), muscular strength (significant increase in the number of push-ups, increase in quadriceps extension strength), and body composition (significant decrease in percent leg fat, significant increase in pelvic bone mineral content).
We found no negative side effects of exercise on a centrifuge for eight weeks. On the contrary, subjects complained of no discomfort (with the exception of muscle soreness), and found exercising on a centrifuge to be somewhat enjoyable. Of the nine subjects who enrolled in the study, eight of them completed the study.

Stepping on the centrifuge resulted in consistently high foot forces of on average 83% body weight, with session averages reaching as high as 124% body weight (Figure 48). Foot forces when walking on Earth are approximately 140% body weight [20].

Figure 47. Maximum number of steps that the subjects could do in two minutes. Subjects significantly improved their performance in this upright test.
Figure 48. Foot forces during exercise sessions; an average for each subject over all sessions is shown, and the average over all subjects was 83% body weight. Inset gives typical force profile during stepping for one foot.

6.1.3 General observations

Experiment 1 was extremely relevant in the context of artificial gravity implementation. We addressed the question of necessary centrifuge radius: can people tolerate a nearly 100% g-gradient? Importantly, we directly measured the effect of exercise on this g-gradient tolerance. Evidently, the question of centrifuge radius becomes less relevant when the subject is exercising; within the range tested here, g-gradient no longer significantly affects the heart rate response to centrifugation. Experiment 2 gives evidence that exercise on a centrifuge may be beneficial, as well, in terms of maintaining or improving fitness. We found that, not only do subjects improve in a similar manner to an upright exercise program, but centrifuge exercise is no less tolerable than upright exercise. Based on these two observations, it seems that considering centrifugation without exercise is illogical and certainly suboptimal – the astronauts may need to exercise, and if this is the case, they should be given the opportunity to exercise in a manner that may improve their fitness.
6.2 Future work

Future work with a tilting centrifuge such as the one used in Experiment 1 should be used to further clarify the g-level and g-gradient tolerances of subjects. For example, two subjects in our study began to show presyncopal symptoms when spun at 1.4-g at the heart. Such a study might ask: what g-levels are typically tolerable, at what tilt angles? Does g-gradient continue to matter at very high g-levels? Would light exercise continue to have such a mitigating effect when the subject was spun at very high g-levels and/or g-gradients? Anecdotally, the aforementioned subjects who began to feel lightheaded, nauseous, and lose peripheral vision, felt considerably relieved when asked to step in place. At what point does stepping in place cease to make high-stress centrifugation tolerable?

To further investigate fitness benefits of stair-stepping on a centrifuge, several additional investigations are recommended. First, the experiment performed here should be extended in time (12-16 weeks) and include female subjects; the number of subjects should also be increased. Second, an upright exercise group should be tested simultaneously with the centrifuge exercise group, in order to directly compare benefits of upright exercise with centrifuge exercise. Perhaps most importantly, a future experiment should investigate the long-term effects of stair-stepping exercise on subjects in bedrest. As outlined in Chapter Two, previous studies have indeed begun to explore the effectiveness of centrifuge exercise on deconditioned bedrest subjects. A future study should look into stair-stepping specifically, and increase the duration of these studies so as to carefully track the protection of bone, muscle, and cardiovascular health.

6.3 Applications

The future of spaceflight, including long-duration interplanetary missions, will require extensive preparation in all technical disciplines associated with these journeys. At the core of these studies must be the health of the crewmembers, as the success of any crewed mission will require safe return of healthy astronauts. All aspects of their health must be predicted at all stages of the mission, and, importantly, we must be prepared with countermeasures for health problems that will probably occur. This thesis has begun to
look into the feasibility and effectiveness of one such countermeasure: exercise in an artificial gravity environment. Evidence from these studies indicate that it is not only feasible, but a potentially very effective countermeasure to known deconditioning. Such a countermeasure may ensure the health and comfort of the crewmembers, and enable successful long-duration spaceflight.
References


REFERENCES


83. Schaffner, G., et al., Effect of load levels of subject loading device on gait, ground reaction force, and kinematics during human treadmill locomotion in a weightless environment, TP-2005-213169, Editor. 2005, NASA.


121. Webster, B.N., *Low magnitude high frequency vibrations applied to the foot through the pedal of a human powered artificial gravity (HPAG) cycle*. MS, 2006, MIT: Cambridge, MA.


146. Bevegard, S., A. Holmgren, and B. Jonsson, Circulatory studies in well trained athletes at rest and during heavy exercise. With special reference to stroke


Appendix A

Centrifuge hardware development

This section outlines hardware developments that were required for Experiment 2 (see Chapter Four); the foot force plates (Section A.3.1) were also used for Experiment 1 (Chapter Three). The appendix will cover support hardware required to prepare the centrifuge for the extra forces of exercise, other hardware to promote the exercise experiment, and instrumentation used during the experiment.
A.1 Support hardware

A.1.1 Footplate

A 0.6 cm (¼”)-thick aluminum footplate was built to accommodate the forces of exercise. For full documentation, see [116]. Four quick-release high shear load pins were used to attach the footplate to the side panels of the centrifuge bed, and allowed the distance of the footplate to be adjusted along the length of the bed, to accommodate subjects of different heights. The pins were 3.2 cm (1.25”) long with 0.6 cm (¼”) diameter with a double shear load rating of 36475 N (8200 lbs), see Figure 50. The subject’s heel was fixed at a height of approximately 23 cm from the bed of the centrifuge and approximately 8 cm above the plane of the subject’s back.
Figure 50. Quick release pins used to secure the new footplate to the centrifuge. Image from www.mcmaster.com, accessed 18 February 2008.

Figure 51. (a) Old and (b) new footplates. The old footplate was 20.3 cm (8”) tall and less than 0.6 cm (1/4”) thick. It was secured with wingnuts through slots on the side of the centrifuge. The new footplate is 58.4 cm tall (23”), and 0.6 cm (1/4”) thick. It includes vibration damping U-bolts to secure the stair-stepper, and high shear-load pins are used to secure it to the centrifuge through holes in the sides.

A.1.2 Steel base plate

A 1.6 cm (5/8”)-thick steel base plate was attached to the concrete floor of the room using 1.3 cm (1/2”)-bolts with anchors; a large Hilti® drill was used to drill holes in the concrete. The shaft supports and centrifuge motor were then attached to this steel plate.

A.1.3 Supports around shaft

Four 42 cm (16 5/8”) long steel corner braces were mounted around the centrifuge support shaft, to the steel base plate. These braces significantly reduced any sway in the support shaft during rotation, and the subject on the centrifuge experienced less vertical motion.
A.2 Other hardware

A.2.1 Frame for DVD player

For the subjects’ entertainment during exercise, a DVD player was mounted to the centrifuge frame in front of them (Figure 52). The aluminum frame was custom built for the DVD player (Digital Labs Model DL730-PD®). Wingnuts and wing-head screws were used to attach the DVD frame to the centrifuge frame, which had to be removed to switch DVDs. The frame allowed subjects to manipulate the player, including volume control.

![DVD player setup](image)

Figure 52. Subject’s view during exercise. The DVD player and heart rate monitor were within arm’s reach. A small reading light allowed the subject to see the heart rate monitor when the room is dark.

A.2.2 Centrifuge back-slider

A sliding mattress was constructed. For full documentation, see [115]. The subject could use this mattress to move radially along the centrifuge bed surface during exercise. The slider includes shoulder pads, against which the subject was able to push, which allowed them to use the stepper with more force.

For this experiment, the slider was fixed in position (not allowed to slide radially).
A.2.3 Resistive arm bands

The resistive armbands had to be attached to the back-slider at two points of attachment near the hips, but the method of attachment had to be such as to not wear at the rubber of the armbands.

We used cushioned metal loop straps to attach the armbands in two places near the subject’s hips. Each loop was placed around two layers of rubber tubing, placed over the resistive armbands. The loops were rigidly clamped using a screw and nut, and an additional wingnut was used for the attachment to the back-slider. In this way, each resistive armband could be easily switched out for another resistance level, using only the wingnuts, and leaving the rest of the rubber hose/metal loop assembly in place (Figure 53).

(a)  
(b)

Figure 53. (a) Cushioned metal loop strap (www.mcmaster.com, accessed 19 March 2008). (b) One of the two attachments of the resistive armband.

A.2.4 Safety belt

A safety belt was mounted rigidly to the centrifuge back-slider. This did not inhibit exercise in any way.
A.3 Instrumentation

A.3.1 Foot force plates

In order to measure foot forces, we custom built 1.9 cm (3/4”) -thick aluminum force plates. We first disassembled Contek® digital bathroom scales and removed the strain gauges and signal wiring. We mounted each set of four strain gauges onto 30x15 cm (12”x6”), 0.6 cm (1/2”)-thick aluminum plates, into which were milled spaces to accommodate the strain gauges, wires, and circuit boards (Figure 51a). After these electronics were carefully placed into the milled spaces, a second, 0.3 cm (1/8”)-thick plate was laid over the base plate (identical spaces were milled into this plate) and screwed in place. This created a “sandwich” that rigidly fixed the strain gauges at their edges, but still allowed deflection of the active part through the milled holes (Figure 54b).

Figure 54. (a) Bottom plates of force plate assembly, with circuit board, strain gauges, and wires carefully placed into the milled spaces. (b) Second plates of the assembly laid over the plates shown in (a), and rigidly screwed in 20 places. Also note the four countersunk holes, which are used to attach this part of the assembly to the stepper.
The bottom assembly was mounted to the stair-stepper before proceeding, using flat-head screws through the four holes seen in Figure 54b. Then, two sets of four spacers were placed on the bottom assembly (Figure 55). The strain gauge spacers (red arrows) were designed to allow the top plate (explained below) to deflect each strain gauge uniformly, without putting any pressure on the rest of the assembly. The limit spacers (green arrows) were designed to inhibit the top plate from being pressed too close to the bottom assembly, therefore damaging the strain gauges.

The top plate was attached to the bottom assembly. First, it was attached at each strain gauge through the spacers (red arrow); in this way, the top plate was rigidly attached to the strain gauges, with the result that pressing on the top plate deflected the strain gauges. Second, it was attached loosely to the bottom plate through the holes beneath each limit spacer (green arrow). Specifically, the holes in the bottom assembly were tapped, but the hole in the top assembly was a loose through-hole, so that the screw could pass easily through it. As such, the screw acted as a
limit in the *other* direction, so that the top plate could not be pulled away from bottom assembly with much force (which, again, could damage the strain gauges). See Figure 56. Finally, plastic footholds were mounted to the top plate to loosely limit movement of the subject’s foot on the plate; in particular, the heel holds helped the subjects’ feet not to slip when they were exercising in the supine position.

The voltage signal and power required were communicated through the parallel port seen at the top of the plates in Figure 54 and Figure 55. For each footplate, the voltage was the sum total of all four strain gauges.

![Figure 56. Side view of heel-side of final force plate assembly. The green arrow points to the limit spacer and screw; the spacer limits the top plate from being pushed down too far, while the screw limits the top plate from being pulled up too far. The red arrow points to the approximate location of one strain gauge, which is obstructed from view.](image)

Calibration was achieved by placing various known masses on the footplate, and recording the voltage output. The regression was highly linear ($r^2 > 0.90$), and allowed for linear conversion of voltage to mass (kg).

### A.3.2 Stepper potentiometer

In addition to force plates, a rotary potentiometer was mounted to the stepper (with both force and displacement, total work rate could be calculated). In the mini-stepper stock design, each stepper arm was mounted to a cylindrical steel shaft on the toe-end of the stepper arm. The shaft was fixed relative to the movement of the stepper, so we chose to use it as the mount for the
potentiometer, to which we also attached a stainless steel bar that was fixed to one stepper arm (and rotated with respect to the shaft.

We used a lathe to carefully create a 1.9 cm (0.75”)-diameter aluminum mount. See Figure 57a. One side of the aluminum mount fit over the stepper shaft, while the other side fit over the potentiometer shaft (which was 0.64 cm (0.25”) in diameter – see Figure 57b). The stainless steel bar was fixed to the potentiometer through its larger (0.95 cm (0.375”)) hole, using two counter-rotated nuts. A small arm was press fit into the stainless steel bar, to eventually attach it to the stepper arm. The potentiometer/bar assembly was then fixed into the aluminum mount, using a set screw. To this assembly was attached a 6-circuit terminal block, which was used for both the potentiometer and the force place wiring and allowed for a power source (from the main batteries of the centrifuge). See Figure 57c.

The fixed shaft of the stepper is seen in Figure 57d. The whole potentiometer assembly was fixed to this shaft using a second set screw, and the small arm at the end of the stainless steel bar was fitted into a hole in the moving stepper arm (Figure 57e). In finality, the aluminum mount was fixed with respect to the stepper shaft, and the stainless steel bar rotated along with the stepper arm, which rotated the potentiometer shaft and resulted in a voltage output.
Figure 57. (a) Drawing and photo of aluminum mount. (b) Drawing and photo of stainless steel bar. (c) Side view of potentiometer, to which is attached a stainless steel bar, to which is attached the aluminum mount. Notice at the left side of the bar a small arm that has been press-fit to the stainless steel bar. (d) Fixed shaft of the stair-stepper. (e) Final potentiometer setup.
A.3.3 VO2000

A MedGraphics VO2000® system allowed measurement of respiratory parameters. The system includes a neoprene face mask that covers the mouth and nose, a plastic bi-directional pneumotach, inserted through a hole in the neoprene at the level of the mouth with a connection to the main unit. Output included oxygen uptake ($\dot{V}_o$, mL/min), carbon dioxide output ($\dot{V}_c$, mL/min), respiratory exchange ratio, respiration rate (breaths/min), minute ventilation (rate of volume flow in and out of the lungs, in L/min), and heart rate. All measurements were collecting using the BreezeSuite 6.2C® software included with the VO2000 system. One data sample was given per breath.

A.3.4 Heart rate monitors

In the original experiment design, a Criticare 504-US® 3-lead ECG was used to deduce heart rate during the exercise sessions. An output voltage signal was recorded by the onboard computer and software developed in-house (Section A.4) and later analyzed for heart rate using peak detection (similar to the blood pressure method, outlined in Chapter Four).

After the pilot subject, we switched to an Acumen TZ-max 100® heart rate monitor. A continuous output signal was not recorded, but the wristwatch receiver recorded an average heart rate over a specified period of time (activated by the subject after warm-up, and stopped before cool-down).

A.3.5 Blood pressure

Beat-to-beat blood pressure was measured using a Portapres® model 2.0 system during measurement sessions (it was not on the spinning centrifuge). The Portapres utilizes a small inflatable finger cuff and pump, and inflates slightly with every pulse beat, to measure pressure at all times. Specifically, the Portapres consists of the finger cuff, main belt unit consisting of batteries, flash memory card (not used), electronics board, and pump, a central unit (interface for control of the whole unit), and analog signal output box containing eight BNC connectors for various signals. We recorded these signals using simple computer software developed in-house (Section A.4). The output is given as a voltage with standard calibration of 100mmHg/V. For this experiment, we recorded (1) pressure waveform, and (2) mean pressure.
A.3.6 Power supplies

UPS® power supply units were used for onboard centrifuge power. They were connected to a wall outlet (115V/60Hz) at all times when not spinning. They provided outlets for three AC plugs providing a maximum of 300W, as well as a ground and power connector providing 24 V DC power. The DC power from one power supply unit was connected to a DC to DC power supply (Orion-300DX/24®). This power supply unit provided a maximum of 300W, with connectors for +/-5V and +/- 12V. This allowed us to power a variety of devices.

A.4 Onboard computer

A CPU onboard the centrifuge allowed for measured of signals during centrifugation or when the centrifuge was static. The computer was a Dell Dimension 2400®, Pentium 4 processor, running Windows XP. Data acquisition software developed in-house by Thomas Jarchow allowed for simultaneous measurement of up to 16 input devices at a sampling rate of 1000 samples/second, and the software interface allowed the operator to monitor the signals on the onboard computer screen. The data was recorded and saved to the onboard computer, and later processed (see Chapter Four).
Appendix B

Considerations for a centrifuge on a spacecraft

This report addresses some of the logistical issues surrounding the use of a short-radius centrifuge in space, e.g. installed in some spacecraft. For the following questions, I will some example data from our centrifuge. Please note that the xyz-axis system here is spacecraft-fixed.

B.1 How much energy does it take to spin up the centrifuge?

Starting from rest, the centrifuge begins with no potential energy or kinetic energy, so the total energy needed to spin up the centrifuge is just the change in kinetic energy. Initial kinetic energy is 0, and final kinetic energy is

\[ K.E. = \frac{1}{2} I_2 \omega_z^2 \]

Equation 5

Let us let define the coordinate system: allow the origin to be located at the axis of rotation, in the plane of the bed of the centrifuge. The centrifuge rotates about the z-axis, in the spacecraft-fixed xy-plane (see Figure 59; note that the axes in the upper right hand corner are displaced from their origin, which is located at the point where \( F_x \) and \( F_y \) meet). The angular
velocity is solely in the z-direction, so the only component of the moment of inertia with which we are concerned is the moment parallel to the angular velocity, the \( z \)-component.

In order to calculate the moment of inertia of the centrifuge, we will break it up piecewise into its major components: the centrifuge bed itself, the footplate that contains the stair-stepper, the slider on which the subject lies, the subject, and the counterweights and power supplies on the side of the axis opposite the subject. We can calculate the moment of inertia of each of these elements, using the equations for flat plates:

\[
I_{zz} = m\left(\frac{1}{12}(a^2 + b^2) + d^2\right)
\]

where \( m \) is the mass, \( a \) and \( b \) are the side lengths, and \( d \) is the distance from the center of mass to the axis of rotation.

<table>
<thead>
<tr>
<th>Table 11. Centrifuge components and moments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
</tr>
<tr>
<td>Centrifuge bed</td>
</tr>
<tr>
<td>Footplate and stair stepper</td>
</tr>
<tr>
<td>Slider</td>
</tr>
<tr>
<td>Subject</td>
</tr>
<tr>
<td>Counterweights</td>
</tr>
<tr>
<td>Power supplies</td>
</tr>
<tr>
<td>TOTAL</td>
</tr>
</tbody>
</table>

Note that this places the center of mass of the centrifuge 0.119 m from the center.

Therefore, using an example rotation rate of \( \omega_z = 30 \text{ RPM} \) (or \( \pi \text{ rad/s} \)), the kinetic energy to spin up the centrifuge is:

\[
\frac{1}{2} I_z \omega_z^2 = 2364.8 \text{ J}
\]

Equation 6

At an arbitrary acceleration rate of 1 degree/s^2, this results in the following energy profile:
In order to keep the spacecraft from rotating in the opposite direction, the required energy compensation is equal and opposite to this during spin-up and spin-down, and must be applied over the length of time that it takes to spin up/down the centrifuge. There are several ways to provide this energy compensation.

1. Thrusters could be implemented on the spacecraft, oriented to provide a spacecraft spin in the direction opposite the centrifuge, about the same axis. The thrusters would produce a constant force over the amount of time required to accelerate the centrifuge.

2. Another centrifuge with the same moment of inertia could be mounted along the same axis, and accelerate in the opposite direction as the other centrifuge, but with the same magnitude.

**B.2 How much energy does it take to keep the centrifuge going?**

Once the centrifuge has accelerated to its final angular velocity, we can draw a free-body diagram to determine the reaction forces and moments that the centrifuge exerts on the spacecraft:

![Energy profile for centrifuge spin-up. This is also the required energy compensation, acting in the opposite direction.](image-url)
Given the assumption that all components of the centrifuge are approximately in the plane of rotation (we can deal with non-plane-of-rotation components shortly), we see that there is in fact no moment exerted by the centrifuge on points of contact.

However, there are linear force reactions to the radial forces caused by centrifugal forces. In the free body diagram above, the forces $F_x$ and $F_y$ are equal to the sum of the centrifugal forces of each of the components of the centrifuge, in the direction of either $F_x$ or $F_y$. In order to simplify the following equations, we will create the scaler variable $F_{AG}$ such that:

$$F_{AG} = m_{slider}r_{slider} \omega^2 + m_{suby}r_{suby} \omega^2 + m_{bed}r_{bed} \omega^2 + m_{fpl}r_{fpl} \omega^2 - m_{cw}r_{cw} \omega^2 - m_{power}r_{power} \omega^2$$

Equation 7

Using the values in Table 1 and $\omega = 30$ RPM, we find that $F_{AG} = 452.1$ N.

We can find the scaler values of $F_x$ and $F_y$ at any given time $t$:

$$F_x = F_{AG} \cos(\omega t)$$
$$F_y = F_{AG} \sin(\omega t)$$

Equation 8

Using the values from Table 1, we can graph these forces:
Figure 60. Radial forces in the x- and y-directions for the centrifuge spinning at 30 RPM. The forces are 90 degrees out of phase with one another, such that when the force in one direction is 0, the force perpendicular to it is at a maximum.

The term $\alpha$ is just the position angle of the centrifuge with respect to some reference, in our case a reference lined up with $F_x$ in the free body diagram (Figure 59).

Since presumably the centrifuge will not lie at the center of mass of the spacecraft, these forces $F_x$ and $F_y$ will cause a moment about the center of mass of the spacecraft. We can visualize this is using a simplified free-body diagram in which the spacecraft is represented by a cylinder:
Figure 61. Free body diagram of a simplified spacecraft; the centrifuge would be located at the point where $F_x$ and $F_y$ meet. The axes in the upper right hand corner or translated from their actual position, which would be centered at the centrifuge.

The moment will be about the center of mass, in some direction in the $xy$-plane. Breaking the moment into its $x$- and $y$-components,

\[
M_x = F_y d \\
M_y = F_x d
\]

Equation 9

where $d$ is the distance from the center of mass of the spacecraft to the centrifuge. The resulting angular acceleration of the spacecraft, $\alpha_{ISS}$, can also be found using the above equations (since in general $M = I\alpha$ when all components are about the same axis).

\[
\alpha_{x,\text{spacecraft}} = \frac{M_x}{I_{x,\text{ISS}}} \\
\alpha_{y,\text{spacecraft}} = \frac{M_y}{I_{y,\text{ISS}}}
\]

Equation 10

Thus, there is a moment imposed on the spacecraft, and a resulting angular acceleration, as seen in Figure 61. These moments are due to the forces $F_x$ and $F_y$. However, as we see in Figure 60, these forces balance themselves out – that is, the net effect of each sinusoidal force is zero. $F_x$ and $F_y$ dictate the magnitude of the moments (Equation 9), which dictate the angular
displacements of the spacecraft (Equation 10), so the net effect of these sinusoidal effects is also zero.

There will be an oscillatory effect due to $\alpha_{x,\text{spacecraft}}$ and $\alpha_{y,\text{spacecraft}}$, but it will not cause the spacecraft to spin.

The instantaneous angular velocity of the spacecraft about the $x$- and $y$-axes due to the centrifuge are perpendicular to the constant angular velocity of the centrifuge (about the $z$-axis). Therefore, the centrifuge does not transfer angular velocity to the spacecraft. Momentary gyroscopic moments may be applied (Equation 25), but they will be balanced the same way that the angular displacements are balanced (a sinusoidal effect, with a net effect of zero).

By conservation of momentum, neglecting friction, we expect the centrifuge to continue rotating in the same direction and with the same angular velocity, with no need to additional energy to keep it spinning.

**B.3 How would friction affect centrifuge rotation and spacecraft attitude rate?**

Above it was stated that once the centrifuge achieved a constant angular velocity, no energy would be needed to keep in spinning. These calculations were made neglecting friction. In reality, two friction effects should be considered: air friction and bearing friction.

**B.3.1 Air friction**

The equation for drag is as follows:

$$\frac{1}{2} \rho v^2 AC_d$$

Equation 11

where $\rho$ is the viscosity of air (1.225 kg/m$^3$), $v$ is the velocity, $A$ is the area of the sidewall of the centrifuge (length times width), and $C_d$ is the coefficient of drag (estimated here to be 1). We
will calculate two separate “drags”, for the two ends (short and long) of the centrifuge, using the mean velocity of the center of each of the sidewalls \(\omega r\), using the mean value of \(r\).

\[
F_{d,\text{long side}} = 0.5(1.225)(\pi*1)^2(2*0.15)(1) = 1.81 \text{ N at 1 m distance} \\
\Rightarrow 1.81 \text{ N*m}
\]

\[
F_{d,\text{short side}} = 0.5(1.225)(\pi*0.5)^2(1*0.15) = 0.227 \text{ N at 0.5 m distance} \\
\Rightarrow 0.11 \text{ N*m}
\]

Therefore the total additional moment due to air friction is \(1.81 + 0.11 = 1.92 \text{ N*m}\).

**B.3.2 Bearing friction**

Bearing friction depends on the type of bearing, but a good estimate for the coefficient of friction of ball or roller bearings is 0.1 (www.bearings.machinedesign.com, accessed 05 May 2007.) The equation for dynamic friction force is:

\[
F_f = \mu N
\]

\text{Equation 12}

where \(\mu\) is the coefficient of friction (0.1) and \(N\) is the force normal to the friction force. In this case that force is equivalent to \(F_{AG}\), calculated above (Equation 7) to be 452.1 N. Therefore the force of friction is \(45.2 \text{ N}\).

Since the width of the rotation shaft is approximately 10 cm, the location of this force is approximately 0.05 m away from the center of rotation, resulting in a net moment of \(2.26 \text{ N*m}\).

The total moment due to air and bearing friction is therefore \(1.92 + 2.26 = 4.18 \text{ N*m}\).

Now that we know both the air friction and bearing friction values, we know that there will be a need for some energy input to the centrifuge, or it will spin to a stop. In fact, we know how soon the centrifuge would spin to a stop without the assistance of the motor. As with linear velocity and acceleration,
where $\alpha$ is the angular acceleration; here we are interested in solving for $t$, the time it takes to spin the centrifuge down to 0 angular velocity ($\omega_f = 0$). We need to first find $\alpha$, which is equivalent to the linear acceleration divided by a given distance. Recalling that our total moment due to air and bearing friction is 4.18 N*m, we know that, equivalently, that the force at 1 m is 4.18 N. Dividing by the total mass of the centrifuge (408.6 kg), we get the acceleration at 1 m radius: $a = 0.01 \text{ m/s}^2$. This also gives us $\alpha = 0.01/\text{s}^2$. Assuming the centrifuge is initially spinning at 30 RPM ($\omega_i = \pi/\text{s}$), we can now solve for $t$ and find that the time it takes for the centrifuge to spin to a stop due to friction is 307 s, or 5 min, 7 sec.

If no compensation is added, this moment of 4.18 N*m will act on the spacecraft itself. Specifically, the spacecraft will begin to rotate about its z-axis in the direction opposite the centrifuge. Let the mass of the spacecraft be $m_{sc}$, and note that the moment will be a force acting at a distance of 0.05 m from the center of rotation of the centrifuge (which we are also taking to be the center axis of the spacecraft). We know that equivalently, 

$$4.18 \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} = \left( m_{sc} \right) \text{kg} \cdot (0.05) \text{m} \cdot (a_{sc}) \frac{\text{m}}{\text{s}^2}$$

Equation 14

where $a_{sc}$ is the linear acceleration at a distance of 0.05 m from the center of rotation. Given these values, the angular acceleration of the spacecraft ($\alpha_{sc}(0.05) = a_{sc}$) is found to be $1672/m_{sc}$. Using the mass of the International Space Station (213,800 kg), we find that $\alpha_{sc} = 0.0078/\text{s}^2$. This is equivalent to saying that after 1 minute, the spacecraft would be rotating at 4.47 rpm.

To prevent this from happening, the centrifuge motor must output an energy of 4.18 J. This will keep the centrifuge spinning at a constant velocity. Additionally, since the motor's reaction torque is in the opposite direction of the centrifuge friction, it will also cancel out the moment acting on the spacecraft due to friction, which would eventually cause it to spin.
B.4 What kind of disturbance will exercise cause?

Exercise is an additional radial force, which must be added to the centrifugal forces of each of the centrifuge components. For this discussion we will consider the forces due to stair-stepping. There are two additional forces due to this type of exercise:

1. The up-and-down motion of the body and resulting cyclical change in \( r_{\text{body}} \), which changes, and
2. The foot forces when stepping.

Let us assume the subject moves up and down (along the long-axis of the centrifuge bed) approximately 5 cm per step, and that the subject steps at an arbitrary frequency of 2.5 Hz. Therefore, the new AG force due to subject movements is:

\[
m_{\text{subj}} \left( r_{\text{subj}} + 0.05 \sin(\omega_{\text{stepping}} t) \right) \alpha^2
\]

Equation 15

where \( \omega_{\text{stepping}} \) is just 15.7 (\( \omega_{\text{stepping}} = 2\pi f_{\text{stepping}} \), where \( f_{\text{stepping}} = 2.5 \) steps/second), and \( t \) is time.

Let us also assume that he steps with a force of approximately 85% body weight (a reasonable assumption, experimentally determined on our centrifuge) and that his body mass is 78 kg. Therefore, an additional force due to stepping is:

\[
F_{\text{step}} \sin(\omega_{\text{stepping}} t)
\]

Equation 16

Now, the previously determined \( F_{\text{AG}} \) should be calculated as outlined below (exercising effects are underlined):

\[
F_{\text{AG}} = m_{\text{slider}} r_{\text{slider}} \alpha^2 + m_{\text{subj}} \left( r_{\text{subj}} + 0.05 \sin(\omega_{\text{stepping}} t) \right) \alpha^2 + m_{\text{bed}} r_{\text{bed}} \alpha^2 + m_{\text{fpl}} r_{\text{fpl}} \alpha^2 - m_{\text{cv}} r_{\text{cv}} \alpha^2
- m_{\text{power}} r_{\text{power}} \alpha^2 + F_{\text{step}} \sin(\omega_{\text{stepping}} t)
\]

Equation 17
Given the example data above, the force $F_{AG}$ now varies sinusoidally, rather than being a constant value as in the non-exercising case (Equation 7). This is pictured in Figure 62:

![Figure 62. Magnitude of the reaction force on the centrifuge, with the subject exercising.]

The forces $F_x$ and $F_y$ will also be more complicated now, since they take into account both the frequency of rotation and the frequency of stepping. They will look like:
The shape of the graph, of course, will vary with the frequency of stepping. That is because the graph takes into account both rotation rate of the centrifuge (0.5 rotations/s) and the stepping frequency of the subject (2.5 steps/s). As with Figure 60, this figure is a depiction of the values calculated using Equation 8; unlike Figure 60, however, $F_{AG}$ varies with time, resulting in the product of two sine curves.

### B.4.1 Sidenote

Up until now we have assumed that the masses on the centrifuge, as well as the stepping, all take place in approximately the same $xy$-plane. This may not be the case. If the centrifuge were rotating about an axis, supported at both ends in the spacecraft, but the bearing between the centrifuge and the axis were not in the same plane ($xy$-plane) as the center of mass of the centrifuge, then there will be additional, somewhat complicated moments on both the centrifuge supports and on the whole spacecraft. A free-body diagram gives a general idea:
Figure 64. Free body diagram in which the elements of the centrifuge (when spinning) create a moment about the centrifuge rotation bearing. The axes in the upper right hand corner are displaced from their actual location; they should have their origin at the centrifuge rotation bearing, and are spacecraft-fixed (the centrifuge spins about the \( x \)-axis).

There is now a moment about an axis perpendicular to the long-axis of the centrifuge (in the orientation shown here, about the \( x \)-axis) through the point labeled “centrifuge rotation bearing.” This moment takes into account the masses \( m \) of each of the centrifuge components (footplate, subject, slider, counterweights, and power supplies), as well as the centripetal acceleration for each of those components, found by \( r\omega^2 \).

\[
M = m_{\text{flpt}} r_{\text{flpt}} \omega^2 d_{\text{flpt}} + m_{\text{subj}} r_{\text{subj}} \omega^2 d_{\text{subj}} + m_{\text{slider}} r_{\text{slider}} \omega^2 d_{\text{slider}} - m_{\text{cw}} r_{\text{cw}} \omega^2 d_{\text{cw}} - m_{\text{power}} r_{\text{power}} \omega^2 d_{\text{power}}
\]

*Equation 18*

It is straightforward to add the forces of exercise into this equation. The axis of this moment will rotate as the forces \( F_x \) and \( F_y \) do, and will vary as:

\[
M_x = M \cos(\omega t) \\
M_y = M \sin(\omega t)
\]

*Equation 19*

In order to avoid this, the bearing between the centrifuge and its rotation axis must be the same \( xy \)-plane, at the same point along the \( z \)-axis, as the center of mass of the centrifuge.
B.5 How can you compensate for exercise?

The force due to stepping, as outlined above, is accounted for both by the subject’s body movement and the force of stepping. The force of stepping is produced by the muscles in the subject’s legs, which means that in order to compensate in the same way, we would need an equal and opposite force being generated in the opposite direction.

A much easier way to approach the problem would simply be to have a moving mass on the other side of the centrifuge, which would move some amount greater than 5 cm, in order to compensate for both the moving mass of the subject and the force of stepping. Thus, we must equate the terms in Equation 17 that are affected by stepping with the counterbalancing mass.

\[
m_{\text{mass}} \left( r_{\text{mass}} + r_{\text{movement}} \right) \sin(\omega_{\text{stepping}} t) \omega^2 = m_{\text{subj}} \left( r_{\text{subj}} + 0.05 \sin(\omega_{\text{stepping}}) \right) \omega^2 + F_{\text{step}} \sin(\omega_{\text{stepping}} t)\]

Equation 20

The unknowns in the following equation are \( m_{\text{mass}}, r_{\text{mass}}, \) and \( r_{\text{movement}}, \) and we can use whatever combination is convenient to achieve equality. For this example I will use the same mass as the subject, at the same initial distance distance, and change the value of \( r_{\text{movement}} \) from 0.05 to something greater. Solving for \( r_{\text{movement}} \) with the assumption the \( m_{\text{mass}} = m_{\text{subj}} \) and \( r_{\text{mass}} = r_{\text{subj}}, \) we find that

\[
r_{\text{movement}} = 0.05 + \frac{F_{\text{step}}}{m_{\text{subj}} \omega^2} = 0.89 \text{ m}
\]

Equation 21

Let us check that this compensation works:
Figure 65. Reaction forces with stepping, without stepping, and then with stepping as well as a moving mass compensation device.

Note that the magnitude of the forces $F_x$ and $F_y$ are actually less, since we are in effect “canceling out” the mass of the whole subject, not just his stepping.

Without the moving mass compensation seen in Figure 65, there would be a requirement for additional energy to keep the centrifuge spinning at a constant velocity. The magnitude of the angular momentum $H$ is found by

$$H = mr\omega$$

Equation 22

Mass $m$ stays constant (the mass of the subject), but the distance of the subject’s center of mass ($r$) varies with exercise. Therefore, in order to conserve angular momentum $H$, the angular velocity $\omega$ will change with every step. This is why the moving mass compensation (or, less ideally, a motor) is required to keep the angular velocity constant.
B.6 What are the considerations for orbital changes due to the centrifuge?

Consider that the spacecraft, which contains the centrifuge, is in a circular orbit 400 km above the Earth’s surface (approximate altitude of ISS. We will work with one example configuration in which the rotation axis of the centrifuge is perpendicular to Earth’s surface:

![Spacecraft with centrifuge orbiting about the Earth.](image1)

We have found above that when the centrifuge is spinning at a constant rate \( \omega_z \), there is no moment about the \( z \)-axis. However, there is an angular momentum in the \( z \)-direction, \( H_z = I_z \omega_z \). We calculated above that \( I_z = 479.2 \text{ kg}\cdot\text{m}^2 \), and again \( \omega_z = \pi \text{ rad/s} \), so \( H_z = 1505.45 \) kg\cdot\text{m}^2/\text{s}.

Now we must also take into account the fact that the spacecraft is orbiting Earth. To simplify our calculations, let us allow the \( xyz \)-axes to be spacecraft-fixed and have their center at the Earth’s center, and to move with respect to an Earth-fixed \( XYZ \)-axes.

![Demonstration of the spacecraft-fixed (Earth-centered) \( xyz \)-axes, moving with respect to the Earth-fixed (Earth-centered) \( XYZ \)-axes.](image2)
It is necessary to know the angular velocity of the spacecraft about the Earth, $\Omega_y$. The distance from the center of the Earth is $r = 6378 + 400 \text{ km} = 6778 \text{ km}$. Using the Vis-Viva equation for circular orbits,

$$V_{\text{circ}} = \left(\frac{\mu}{r}\right)^{\frac{3}{2}} = 7.6629 \text{ km/s}$$  

Equation 23

where $\mu = 398,600 \text{ km}^3/\text{s}^2$ is the gravitational parameter of Earth. Then,

$$\Omega_y = \frac{V_{\text{circ}}}{r} = 0.00113 \text{ rad/s}$$  

Equation 24

Because the angular momentum of the spacecraft about the Earth is much, much less than the angular momentum of the centrifuge in the spacecraft, we may neglect that angular momentum for the following calculations.

Now that we are taking into account the spacecraft’s orbit about the Earth, we will have a net moment for the Earth-spacecraft system. In general the following vector equation is true:

$$\sum \vec{M}_o = \left(\dot{\vec{H}}_o\right) + \vec{\Omega} \times \vec{H}_o$$  

Equation 25

In the case in which the centrifuge is spinning at a constant angular velocity, its angular momentum is constant, so $\dot{\vec{H}}_o = 0$. We calculated above that $\vec{\Omega} = \Omega_y = 0.00113 \text{ rad/s}$, and we also found above that $\vec{H}_o = H_z = 1505.45 \text{ kg}^*\text{m}^2/\text{s}$. Since we are taking the cross product of $\Omega_y$ and $H_z$, the moment will be in the $x$-direction:

$$\sum \vec{M}_o = M_x = 1.70 \text{ kg}^*\text{m}^2/\text{s}^2 = 1.70 \text{ N}^*\text{m}$$  

Equation 26
Physically, it appears that there will be a moment acting to alter the inclination of the orbit about the \(x\)-axis. In order to avoid this, it would be necessary to either implement a thruster acting in the opposite direction, or to implement an identical centrifuge acting in the opposite direction, which would have the opposite angular momentum and so the net moment about the \(x\)-axis (and all other axes) would be zero.

There are two maneuvers that will change this moment. First, say we intend to make an orbital change that increases or decreases the altitude of the spacecraft (changing \(r\)). In order to change the altitude \(r\), one must apply some \(\Delta V\) (a change in \(V_{\text{circ}}\)), which then changes \(\Omega_y\), and finally the net moment \(M_x\). Second, during spin-up and spin-down of the centrifuge, \(\dot{H}_0 \neq 0\) and will about the \(z\)-axis; therefore the net moment will have components about the \(x\)-axis and the \(z\)-axis.

Again, both of these issues could be circumvented with an equal-and-opposite rotating centrifuge.
Appendix C

Informed consents
C.1 Informed consent for Experiment 1

CONSENT TO PARTICIPATE IN
BIOMEDICAL RESEARCH

Effect of Body Tilt on Rest and Exercise on a Short Radius Centrifuge

You are asked to participate in a research study conducted by Laurence Young, ScD, Thomas Jarchow, PhD, and Jessica Edmonds, SM, from the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (M.I.T.), collaborating with the University of Antwerp (Prof. Floris Wuyts, Robby Vanspauwen). You have been asked to participate in this study because you have volunteered and meet the minimum health and physical requirements for this study. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- PARTICIPATION AND WITHDRAWAL

Your participation in this research is completely VOLUNTARY. If you choose to participate you may subsequently withdraw from the study at any time without penalty or consequences of any kind. If you choose not to participate, that will not affect your relationship with M.I.T. of the University of Antwerp, or your right to health care or other services to which you are otherwise entitled.

- PURPOSE OF THE STUDY

The purpose of the study is to determine the physiological effects of resting and of exercise at various rotation rates and various tilt angles on a short-radius centrifuge. This study will systematically vary both rotation rate and the tilt of the centrifuge platform, while you are at rest or exercising, in order to measure cardiovascular parameters and better match upright responses.
• PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

This experiment has two parts, which may be done consecutively or on separate days. The duration of the experiment will be approximately two hours; one hour per part. In the first protocol you will be not exercising, and in the second protocol you will be exercising either using a stepper device (described below) or by stepping in place.

You will arrive at the lab and be thoroughly briefed on all of the centrifuge equipment, the exercise device, and all measurement devices.

-The centrifuge, located at the University of Antwerp, Belgium, is an approximately two meter radius centrifuge with four arms. Two of the arms are beds, and two are chairs. The beds will be used for this study. When you are lying on the bed with your head towards the center of rotation, you will feel a footward force when the centrifuge spins, which increases as centrifuge velocity increases. The centrifuge is capable of rotating up to 45 RPM.

-The exercise device is similar to a stair-stepper. When you are supine, you will place your feet against two small metal platforms. The platforms are attached by resistive bands to a fixed point on the centrifuge and you will step against the resistive force of the bands.

-The measurement devices will include the following. (1) A store-bought heart rate monitor (Polar or Acumen), which is simply a chest strap that sends a wireless signal to the centrifuge onboard computer. (2) A blood pressure monitor (automatic blood pressure cuff or PortaPres device). (3) Foot force plates integrated into the exercise device, also used to measure your postural sway while standing upright. (4) Strain gauges to be placed around your calf, to measure changes in circumference. (5) A spirometer with an attached oxygen sensor, to measure exhaled gas content as well as volumetric flow rate.

- You may be audiotaped in order to monitor their well-being while on the centrifuge.

Experiment Protocol 1.

You will stand upright while all measurements are taken, for approximately five minutes. The upright measurements may include standing on one foot and/or closing your eyes. You will be spotted for this procedure. Then you will lie on the centrifuge bed, while resting measurements are taken for approximately five minutes. The centrifuge will be spun up to five different rotation rates (10 to 45 rpm), and stay at each rotation rate for five minutes while measurements are taken. Then the centrifuge will be spun down until it is still, and the bed tilted up (such that your head is above your feet) to one of two positions (between 15-80 degrees) and again resting measurements will be taken. Then the centrifuge will be spun to the same rotation rates as before, with the bed still tilted, and held at each rotation rate for five minutes. After this, the centrifuge will be spun down until it is still, tilted to the second angle, and the same
procedure repeated. After this spinning portion, the bed will be tilted back to supine, and resting measurements will be taken. You will then be assisted off the bed, and upright measurements will be taken one last time.

Experiment Protocol 2.
This protocol will be identical to Protocol 1, except that you will be exercising for all measurements (upright, supine, supine while spinning, and supine and tilted up while spinning). The exercise will either be using the exercise device described above, or will be simply stepping in place.

- **POTENTIAL RISKS AND DISCOMFORTS**

  - To mitigate risks, you will be strapped into the centrifuge, have audio communication with the investigators at all times, and there will always be a spotter present.
  - You may feel motion sick on the centrifuge. We will help you to minimize motion sickness by instructing you not to move your head. Motion sickness can be minimized or eliminated by holding the head still.
  - You may feel lightheaded and become pre-syncopal (feel as if you might faint) at the higher rotation rates. We will minimize the chance for this to happen by equipping the centrifuge with headsets, so we will be in constant communication with you. Dialogue will be maintained at least every 30 seconds, and you will be asked about your comfort level. If you begin to feel lightheaded, feel your vision narrow, or feel uncharacteristically sleepy, the centrifuge will be slowed down and the experiment terminated.

    The treatment or procedure may involve risks that are currently unforeseeable.

- **ANTICIPATED BENEFITS TO SUBJECTS**

  It is not expected that you will benefit from this experiment.

- **ANTICIPATED BENEFITS TO SOCIETY**

  Benefits to society include a better understanding of exercise and centrifugation as a countermeasure to physiological deconditioning during long-duration space flight. This study may potentially benefit a future astronaut population, such as astronauts on a long trip to Mars.

- **PAYMENT FOR PARTICIPATION**

  You will receive 25 Euros, in cash, upon completion of this experiment.
• **FINANCIAL OBLIGATION**

There is no financial obligation for this study.

• **PRIVACY AND CONFIDENTIALITY**

The only people who will know that you are a research subject are members of the research team and, if appropriate, your physicians and nurses. No information about you, or provided by you during the research will be disclosed to others without your written permission, except: if necessary to protect your rights or welfare, or if required by law.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. The data may consist of measures of your foot pressure, heart rate, blood pressure, and leg circumference, information from the computer on an exercise device, subjective ratings of motion sickness and illusions experienced during centrifugation, and subjective descriptions of your experience during centrifugation.

During the experiment, the experimenter will monitor you through a video camera capable of imaging in darkness. You will be monitored to ensure your state of well-being and compliance with the experiment protocol. In some cases the video data will be recorded on VHS tapes. You have the right to review and edit the tape. Any recorded videotapes will be accessible only by members of the current Artificial Gravity research team. Videotapes will be erased in 5 years, at most.

Research data collected during the experiment will be stored in coded files that contain no personal information. The coding of the data will prevent linking your personal data to research data when it is analyzed or archived. Research data is stored in a database and/or ASCII files, and there is no certain date for destruction. The data is stored in laptops that are accessible only by Artificial Gravity team members. The investigator will retain a record of your participation so that you may be contacted in the future should your data be used for purposes other than those described here.

• **WITHDRAWAL OF PARTICIPATION BY THE INVESTIGATOR**

The investigator may withdraw you from participating in this research if circumstances arise which warrant doing so. If you experience abnormally high heart rate, very high motion sickness levels, narrowing of vision or lightheadedness, or extreme drowsiness or dizziness, or if you become ill during the research, you may have to drop out, even if you would like to continue. The investigators, Dr. Laurence Young, Dr. Thomas Jarchow, and Jessica Edmonds will make the decision and let you know if it is not possible for you to continue. The decision may be made either to protect your health and safety, or because it is part of the research plan that people who develop certain conditions may not continue to participate.
NEW FINDINGS

During the course of the study, you will be informed of any significant new findings (either good or bad), such as changes in the risks or benefits resulting from participation in the research or new alternatives to participation, that might cause you to change your mind about continuing in the study. If new information is provided to you, your consent to continue participating in this study will be re-obtained.

EMERGENCY CARE AND COMPENSATION FOR INJURY

In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the hospital at the University of Antwerp, including emergency treatment and follow-up care as needed. The emergency room of the hospital is located one floor above the experiment laboratory. The cost of such treatment will be covered by the insurance of the university hospital. The University of Antwerp does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by contacting Hildegarde Hermans and Michel Van Mechelen, legal representatives of the University Hospital. The Faculty of Medicine may be reached at +32 3 820 26 37.

IDENTIFICATION OF INVESTIGATORS

In the event of a research related injury or if you experience an adverse reaction, please immediately contact one of the investigators listed below. If you have any questions about the research, please feel free to contact

Principal Investigator:
Laurence Young
77 Massachusetts Avenue
37-219
Cambridge, MA 02139

Co-Investigators:
Thomas Jarchow
77 Massachusetts Avenue
37-219
Cambridge, MA 02139
(617) 253-0017
Jessica Edmonds
77 Massachusetts Avenue
37-219
Cambridge, MA 02139
(617) 258-9730

• RIGHTS OF RESEARCH SUBJECTS

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143B, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.
__SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE__
I have read (or someone has read to me) the information provided above. I have been given an opportunity to ask questions and all of my questions have been answered to my satisfaction. I have been given a copy of this form.

BY SIGNING THIS FORM, I WILLINGLY AGREE TO PARTICIPATE IN THE RESEARCH IT DESCRIBES.

Name of Subject

Name of Legal Representative (if applicable)

Signature of Subject or Legal Representative  Date

__SIGNATURE OF INVESTIGATOR__
I have explained the research to the subject or his/her legal representative, and answered all of his/her questions. I believe that he/she understands the information described in this document and freely consents to participate.

Name of Investigator

Signature of Investigator  Date (must be the same as subject’s)

__SIGNATURE OF WITNESS (If required by COHES)__
My signature as witness certified that the subject or his/her legal representative signed this consent form in my presence as his/her voluntary act and deed.

Name of Witness
C.2 Informed consent for Experiment 2

CONSENT TO PARTICIPATE IN
BIOMEDICAL RESEARCH

Exercise During Artificial Gravity Through Centrifugation

You are asked to participate in a research study conducted by Laurence Young, Sc.D., Thomas Jarchow, Ph.D., and Jessica Edmonds, a graduate student from the Department of Aeronautics and Astronautics Man-Vehicle Laboratory at the Massachusetts Institute of Technology (M.I.T). The results of this study may be published in a student thesis or scientific journal. You have been asked to participate in this study because you have volunteered and meet the minimum health and physical requirements for our study. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

PARTICIPATION AND WITHDRAWAL

Your participation in this research is completely VOLUNTARY. If you choose to participate you may subsequently withdraw from the study at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so. Such circumstances include evidence that you do not meet the minimum health and physical requirements, or that during the study it becomes clear to the experimenter that you are becoming drowsy, unalert, or uncooperative. If you choose not to participate, it will not affect your relationship with M.I.T. or your right to health care or other services to which you are otherwise entitled.

You should not participate in this study if you have any medical heart conditions, respiratory conditions, medical conditions which would be triggered if you develop motion sickness, are under the influence of alcohol, caffeine, anti-depressants, or sedatives, have suffered in the past from a serious head injury (concussion), or if there is any possibility that you may be pregnant. In addition, you should not participate if you have any musculoskeletal, spinal, or other injury that prevents you from participating in low-impact exercise, such as exercise on a stair-stepper machine. The experimenter will check to see if you meet these requirements, by asking you to fill out two questionnaires: “Bone, Muscle, and Joint History” and “AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire” (note that on the screening questionnaire, we do allow physical inactivity and certain prescription medications, which will be discussed with you by your experimenter). You may not be allowed to participate if you are currently participating in a fitness program, since this experiment is aimed at improving your fitness level from a previously unfit state.
• **PURPOSE OF THE STUDY**

The purpose of this study is to implement an exercise device on the short-radius Artificial Gravity (AG) centrifuge. We aim to understand the physiological effects of exercise combined with centrifugation. Short radius centrifugation is currently being investigated as a countermeasure to the deleterious effects of weightlessness experienced during long duration spaceflight, and we are investigating the potential additional benefits of lower body exercise during centrifugation to increase the effectiveness of AG as a countermeasure.

• **PROCEDURES**

For this experiment, you tentatively agree to attend up to 30 exercise sessions. These sessions will be scheduled through the agreement of you and your experimenter. You will be randomly assigned to either an “upright exercise” group, or an “exercise during centrifugation” group. Your tentative commitment is as follows.

- 2-3 measurement sessions, up to two weeks apart, before beginning the exercise program.
- Exercise sessions for up to 10 weeks, on 3-5 days per week. Each exercise session will last no more than one hour, for a total of no more than one and a half hours for exercise plus measurements.
- 1-2 additional measurement sessions, after the second and/or fourth week of exercise, and a final measurement session after the exercise sessions are completed. The total additional measurement sessions (before, during, and after the exercise program) will not exceed six.

Upon arriving at the lab, you will be briefed on the background of centrifugation, disqualifying medical conditions, the experiment protocol, and the various components of the centrifuge, including the emergency stop button, restraining belt, exercise device, and data collection devices. You will be asked to fill out two questionnaires (mentioned above) relating to athletic and medical history. The experimenter may also record your answers to basic questions about your health, and take your height, weight, blood pressure, heart rate, and limb circumferences (using a tape measure).

The devices that may be used to collect data during your experiment include:

- A chest-strap heart rate sensor (over-the-counter - often used by athletes)
- An ECG with a finger pulse oximeter, which will be used to measure heart rate, blood saturation, and pulse pressure. The ECG has three small adhesive pads to which wires are attached, and you will be asked to stick them to the skin on your chest. The finger pulse oximeter is a plastic cuff that will be placed on one of your fingers.
- Force sensors on the footplates – these are simply small scales beneath each footplate, that measure your foot pressure.
- Strain gauges around your calf muscles. These are small elastic bands that will be taped around your legs in various places, and measure changes in your leg circumference during centrifugation and during exercise.
- A blood pressure cuff, such as the automatic type you can buy to monitor your blood pressure. Alternatively, a beat-to-beat blood pressure finger cuff may be used. This
device requires you to wear a belt (the belt contains a small computer) and a fabric finger band that measures the blood pressure at every heart beat, in your finger.

- A spirometer, which measures volumetric flow rate of your breathing. This is simply a small plastic tube with sensors inside, that you place over your mouth while breathing normally in and out.
- A respiration belt, which is an inflated waist band that senses pressure changes. It will be used to measure your breathing rate and the volume of each of your breaths.
- A verbal questionnaire called the “Borg scale”, which you will use to rate your perceived exertion during exercise. You will be instructed about this rating scale before you begin. These devices may be used during measurement sessions and/or during exercise sessions.

Note that ALL MEASUREMENTS are standard medical or exercise physiology procedures.

In addition to the measurement devices described above, the separate measurement sessions mentioned in the first paragraph may include the following collaborators and the following measurements:

- Resting energy expenditure (REE) will be measured at the MIT Clinical Research Center. REE will be measured no more than five times. To determine the number of calories your body burns at rest, you will lie down and breath normally while a clear plastic bubble that fits over your head measures the amount of carbon dioxide that you produce. The measurement will take 20 minutes.
- Dual x-ray absorptiometry (DEXA) will be measured at the MIT Clinical Research Center. This measurement requires you to lie still on a bed while your body is scanned. The scan device itself moves over your body without touching you, and you are not enclosed in a small space. The DEXA scan will be done over the legs, arms, and torso. DEXA will be measured no more than three times.
- A general “fitness assessment”, administered by the Zesinger Sports and Fitness Center. The fitness assessment would measure submaximal oxygen uptake on a specialized exercise bike, body limb circumference, resting blood pressure, resting heart rate, body fat percentage as measured by a skinfold technique, strength and flexibility, recovery rate, and body weight.
- We will measure orthostatic tolerance using a stand test, either in our lab or at the MIT Clinical Research Center. During the test, you will lie supine on a bed for up to 10 minutes, then sit up for up to 10 minutes, then stand for up to 10 minutes. You will sit and stand under your own power. During this time your heart rate and blood pressure will be monitored.
- We will measure the strength of your quadriceps using either an isometric extension configuration (in other words, you push against a fixed plate as hard as you can), or an isokinetic strength testing device (such as a Cybex™, which allows you to extend your leg at a constant velocity, while pushing as hard as you can). If the isometric configuration is used, you will be seated in a chair that is fixed to the ground. With your leg bent at an angle between 90 and 135 degrees, you will be asked to push as hard as you can against a force plate, one leg at a time. You will hold this contraction for up to five seconds. If the isokinetic configuration is used, you will be seated in a chair that is fixed to the ground. You will be asked to extend your leg against a resistance that allows for constant velocity extension. In both cases, the force exerted by your leg will be measured.
We will measure endurance by asking you to stair-step on a stepping machine, upright, as fast as you can for one to three minutes. The number of steps will be counted during than time to determine your endurance.

We will measure your maximal oxygen uptake using a VO2000™ metabolic testing system and a treadmill. The VO2000™ is a fabric face cover, with a hole for your mouth, into which is inserted a plastic tube that contains oxygen and carbon dioxide sensors. You will wear this device while exercising on a treadmill (upright). You will undergo the “Bruce protocol”, while measurements are taken. The “Bruce protocol” will not increase treadmill speeds above 7 miles per hour (you may tell us if you’re uncomfortable with any speed), and will not increase treadmill grade greater than 10 degrees.

We will measure your balance using a standard Sharpened Romberg diagnostic test. You will stand heel-to-toe (feet in a line), with your arms crossed. You will close your eyes, and the experimenter will time your ability to keep your balance (no major movements of your arms or feet). You will not be disturbed during this test.

We may measure your body fat percentage using skinfold calipers, similar to the measurement performed by the Zesinger Center fitness assessment. This measurement will take place at the MIT Clinical Research Center. The calipers is a large blunt tweezer-type object that is used to pinch a large section of your skin, gently, to determine body fat.

During every exercise session you will either lie on the centrifuge in the supine position, with your feet on a stair-stepper mounted to the footplate, or else stand upright on the stair-stepper. Whether you are upright or on the centrifuge, the experimenter may collect some data from you before exercise begins.

If you are on the centrifuge, the experimenter will ask you if you are ready before starting rotation. Your rotation on the centrifuge will not exceed the following parameters:
- Acceleration no greater than 2 rotations per minute, per second (12 deg/s^2).
- Rotation rate no greater than 30 rotations per minute.
- Time of rotation not exceeding 1 hour.

You will begin exercising when you are ready. You may be entertained during the exercise session with music or a video. Exercise may be in the dark and/or in the light. Your level of exercise (speed at which you stair-step or perform knee bends) will be at your discretion, but you will be asked to maintain a target heart rate (65%-85% of your maximal heart rate, as determined by 220 minus your age or your maximum heart rate during the maximal oxygen uptake test on the treadmill, described above.) During the exercise session and after the experiment you will be asked to report your subjective experience (how you feel, how you perceive exercise to be different from exercising in a static upright orientation, etc.), including reporting your perceived exertion using the Borg scale. During and after the experiment you will be asked to report your motion sickness rating. These data will be recorded anonymously.

When the experiment is complete, you will stop exercising and if applicable, the centrifuge will be stopped. The experimenter may collect some additional data from you, including your recovery to within 20% of your resting heart rate, blood pressure, and respiration rate.
• POTENTIAL RISKS AND DISCOMFORTS

During rotation you may develop a headache or feel pressure in your legs caused by a fluid shift due to centrifugation. You may also experience nausea or motion sickness, but this should be minimized due to you holding your head stationary. The experimenter will frequently ask you about your motion sickness to ensure your comfort. You may also feel sleepy during the experiment, and the experimenter will monitor your alertness through communication and through a video camera.

When you use the stair-stepper device during centrifugation, you may experience lateral forces on your knees. You will exercise at your own pace, and if you experience any discomfort, you are free to discontinue exercise at any time.

Your heart rate may increase due to the rotation speed, and it may increase more due to exercise on the centrifuge. Your heart rate will be measured before and after the experiment. For experiments with accelerations of more than 1.0g at the feet, your heart rate will be continuously monitored. The experiment will be terminated if your heart rate goes above the value: (220 – your age) or a maximum of 200 bpm.

Serious injury could result from falling off the centrifuge while it is rotating. You will be restrained by a safety belt, which is to be worn around the waist/chest at all times while the centrifuge is rotating. The centrifuge is equipped with strong side railings similar to those on a hospital bed, which you may use these to stabilize yourself while you exercise if that is more comfortable for you.

You will be continuously monitored by at least one experimenter in the same room. The investigator can also see you through a video camera mounted on the centrifuge, and in this way determine your well-being and the nature of any problems that arise.

You can also terminate rotation at any time for any reason by pressing the emergency stop button.

If you feel lightheaded during the orthostatic stand-test, you may sit down or lie down.

The risk for the isometric or isokinetic quadriceps strength test is a muscle or tendon tear. These risks typically occur in extreme circumstances where maximum force is being developed at maximum contraction, or when trying the complete the test with a pre-existing injury. To minimize this risk, you will have already completed a medical and exercise history questionnaire. If you have a history of current or previous injuries to the joints, bones, or muscles of the lower body, you will not be permitted to take part in the study. In the unlikely case that you perceive any pain or discomfort during the testing, you will be instructed to immediately discontinue the exercise and release the contraction of the muscle.

The risk for the maximal oxygen uptake test on the treadmill and for the upright stair-stepping endurance test is exhaustion. Serious injury could occur from falling off the treadmill. Although the tests are not intended to exhaust you, you may feel as if you can not continue. To
minimize this risk, you will be asked every 20-30 seconds if you wish to continue. If you do not wish to continue, the treadmill will be stopped and the testing discontinued, or if you’re on the stair-stepper, you may voluntarily stop stair-stepping. Additionally, you will have answered questions in the AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire, and if necessary you will be examined by the CRC to determine if beginning an exercise program and experiencing testing such as the Bruce protocol and the upright stepping test is advisable.

The standing balance test could cause you to fall. To minimize this risk, you will be provided a human spotter. You are not expected to experience a decreased level of balance due to this experiment.

The radiation risk associated with a DEXA scan (0.26 µrem) is less than 10% of the annual natural background radiation from the earth and sky. There are no known health risks associated with such a dose.

The procedure may involve risks that are currently unforeseeable.

- **ANTICIPATED BENEFITS TO SUBJECTS**

  You may experience an improved level of physical fitness, as measured by aerobic capacity, muscular endurance, and body weight and composition.

- **ANTICIPATED BENEFITS TO SOCIETY**

  The potential benefits to science and society are a better understanding of how short radius centrifugation combined with exercise can enable long duration spaceflight.

- **PAYMENT FOR PARTICIPATION**

  Eligible subjects will receive payment of $20 per week if you do not finish the study, or $50 per week if you do finish the study. Checks will be mailed within 4-6 weeks of participation. Subjects not eligible for compensation include international students who work more than 20 hours per week, or volunteers from the MIT Man-Vehicle Lab.

- **PRIVACY AND CONFIDENTIALITY**

  The only people who will know that you are a research subject are members of the research team. No information about you, or provided by you during the research will be disclosed to others without your written permission, except if necessary to protect your rights or welfare, or if required by law.
When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. The data may consist of measures of your foot pressure and heart rate, information from the computer on an exercise device, subjective ratings of motion sickness and illusions experienced during centrifugation, subjective descriptions of your experience during centrifugation, and subjective descriptions of your orientation in space.

During the experiment, the experimenter will monitor you through a video camera capable of imaging in darkness. You will be monitored to ensure your state of well-being and compliance with the experiment protocol. In some cases the video data will be recorded on VHS tapes. You have the right to review and edit the tape. Any recorded videotapes will be accessible only by members of the current Artificial Gravity research team. Videotapes will be erased in 5 years, at most.

Research data collected during the experiment will be stored in coded files that contain no personal information. The coding of the data will prevent linking your personal data to research data when it is analyzed or archived. Research data is stored in a database and/or ASCII files, and there is no certain date for destruction. The data is stored in the Man-Vehicle Lab computers that remain accessible only by Artificial Gravity team members. The investigator will retain a record of your participation so that you may be contacted in the future should your data be used for purposes other than those described here.

- **WITHDRAWAL OF PARTICIPATION BY THE INVESTIGATOR**

  The investigator may withdraw you from participating in this research if circumstances arise which warrant doing so. If you experience abnormally high heart rate, very high motion sickness levels, or extreme drowsiness or dizziness, you may have to drop out, even if you would like to continue. The investigators, Dr. Laurence Young, Dr. Thomas Jarchow, and Jessica Edmonds, will make the decision and let you know if it is not possible for you to continue. The decision may be made either to protect your health and safety, or because it is part of the research plan that people who develop certain conditions may not continue to participate.

  If you must drop out because the investigator asks you to (rather than because you have decided on your own to withdraw), you will be paid the hourly amount stated ($10/hr) for the amount of time that you spent as a subject.

- **NEW FINDINGS**

  During the course of the study, you will be informed of any significant new findings (either good or bad), such as changes in the risks or benefits resulting from participation in the research or new alternatives to participation, which might cause you to change your mind about continuing in the study. If new information is provided to you, your consent to continue participating in this study will be re-obtained.
• **EMERGENCY CARE AND COMPENSATION FOR INJURY**

  “In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253 2822.”

• **IDENTIFICATION OF INVESTIGATORS**

  In the event of a research related injury or if you experience an adverse reaction, please immediately contact one of the investigators listed below. If you have any questions about the research, please feel free to contact:

  Principal Investigator:
  Laurence Young
  77 Massachusetts Avenue
  37-219
  Cambridge, MA 02139
  (617) 253-7759

  Co-Investigators:
  Thomas Jarchow
  77 Massachusetts Avenue
  37-219
  Cambridge, MA 02139
  (617) 253-0017

  Jessica Edmonds
  77 Massachusetts Avenue
  37-219
  Cambridge, MA 02139
  (617) 258-9730

• **RIGHTS OF RESEARCH SUBJECTS**

  You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.
SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE
I have read (or someone has read to me) the information provided above. I have been given an opportunity to ask questions and all of my questions have been answered to my satisfaction. I have been given a copy of this form.

BY SIGNING THIS FORM, I WILLINGLY AGREE TO PARTICIPATE IN THE RESEARCH IT DESCRIBES.

________________________________________  __________________________________________
Name of Subject                                                                

________________________________________  __________________________________________
Name of Legal Representative (if applicable)                                     

________________________________________  ______________
Signature of Subject or Legal Representative   Date

SIGNATURE OF INVESTIGATOR
I have explained the research to the subject or his/her legal representative, and answered all of his/her questions. I believe that he/she understands the information described in this document and freely consents to participate.

________________________________________
Name of Investigator

________________________________________  _____________________________
Signature of Investigator    Date (must be the same as subject’s)

SIGNATURE OF WITNESS (If required by COUHES)
My signature as witness certified that the subject or his/her legal representative signed this consent form in my presence as his/her voluntary act and deed.

________________________________________
Name of Witness

________________________________________
Appendix D

Individual subject data, Experiment 1
Missing subject numbers correspond to subjects who did not finish the experiment or who were otherwise excluded from analysis completely.

Data points that were clearly outliers were removed before analysis and are not shown here. In some cases, entire measurements were missing for a subject; for example, RC40 data for Subject 2. Beginning with Subject 7, the maximum g-level was 1.2 rather than 1.4.

Legend

GLEV: g-level measured at the heart, along the body axis
TILT: tilt angle, head over feet, measured from horizontal
RPM: rotation rate (in rotations per minute), required to achieve the desired g-level at the heart
ACT: action, where 0 = standing on one foot (right foot hanging), 1 = standing on both feet, and 2 = stepping in place at 1.5 Hz
B2B: average beat-to-beat interval during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1), in ms
HRT: average heart rate during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1), in beats per minute
SBP: average systolic blood pressure at heart level during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1), in mmHg
DBP: average diastolic blood pressure at heart level during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1), in mmHg
LF: average left foot force during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1), in kg
RF: average right foot force during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1), in kg
RC40: average right calf volume from seconds 40-45 after the beginning of that action, as a percent change from the resting supine value
RC100: average right calf volume from seconds 100-105 after the beginning of that action, as a percent change from the resting supine value (no data for action = 1)
PCTWT: average percent body weight (sum of both foot forces divided by body weight) during the last half of the action (seconds 60-120 for actions 0 and 2, and seconds 30-60 for action 1)
Subject 2

Male

Height = 170 cm

Weight = 68 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.4</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.4</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
</tbody>
</table>
Subject 3

Male

Height = 177 cm

Weight = 83 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>951</td>
<td>63</td>
<td>120</td>
<td>71</td>
<td>12</td>
<td>-3</td>
<td>-0.51</td>
<td>-0.76</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>986</td>
<td>61</td>
<td>120</td>
<td>69</td>
<td>11</td>
<td>1</td>
<td>-0.73</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>792</td>
<td>76</td>
<td>138</td>
<td>84</td>
<td>16</td>
<td>0</td>
<td>-1.51</td>
<td>-1.42</td>
<td>20</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>0</td>
<td>720</td>
<td>83</td>
<td>144</td>
<td>89</td>
<td>68</td>
<td>-1</td>
<td>-0.09</td>
<td>0.24</td>
<td>81</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>1</td>
<td>827</td>
<td>73</td>
<td>133</td>
<td>81</td>
<td>48</td>
<td>45</td>
<td></td>
<td></td>
<td>112</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>2</td>
<td>385</td>
<td>156</td>
<td>153</td>
<td>93</td>
<td>46</td>
<td>34</td>
<td>-0.20</td>
<td>-0.16</td>
<td>97</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>0</td>
<td>685</td>
<td>88</td>
<td>159</td>
<td>97</td>
<td>85</td>
<td>0</td>
<td>1.26</td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>2</td>
<td>541</td>
<td>111</td>
<td>158</td>
<td>92</td>
<td>66</td>
<td>57</td>
<td></td>
<td>1.38</td>
<td>147</td>
</tr>
<tr>
<td>1.4</td>
<td>0</td>
<td>37.7</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>0</td>
<td>37.7</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>0</td>
<td>37.7</td>
<td>2</td>
<td>570</td>
<td>105</td>
<td>165</td>
<td>99</td>
<td>82</td>
<td>81</td>
<td></td>
<td>2.44</td>
<td>195</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>879</td>
<td>68</td>
<td>119</td>
<td>74</td>
<td>27</td>
<td>-2</td>
<td>1.43</td>
<td>1.46</td>
<td>29</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>918</td>
<td>65</td>
<td>123</td>
<td>73</td>
<td>24</td>
<td>8</td>
<td>1.59</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>750</td>
<td>80</td>
<td>131</td>
<td>78</td>
<td>25</td>
<td>9</td>
<td>0.82</td>
<td>0.45</td>
<td>41</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>0</td>
<td>803</td>
<td>75</td>
<td>129</td>
<td>79</td>
<td>54</td>
<td>-1</td>
<td>1.51</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>1</td>
<td>778</td>
<td>77</td>
<td>135</td>
<td>76</td>
<td>36</td>
<td>36</td>
<td>1.68</td>
<td></td>
<td>86</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>2</td>
<td>560</td>
<td>107</td>
<td>140</td>
<td>83</td>
<td>39</td>
<td>30</td>
<td>0.40</td>
<td>0.40</td>
<td>83</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>0</td>
<td>693</td>
<td>87</td>
<td>146</td>
<td>89</td>
<td>78</td>
<td>0</td>
<td>1.88</td>
<td>2.12</td>
<td>93</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>723</td>
<td>83</td>
<td>147</td>
<td>88</td>
<td>59</td>
<td>56</td>
<td>2.10</td>
<td></td>
<td>137</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>2</td>
<td>470</td>
<td>128</td>
<td>161</td>
<td>98</td>
<td>54</td>
<td>46</td>
<td>0.40</td>
<td>0.46</td>
<td>120</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>31.8</td>
<td>0</td>
<td>598</td>
<td>100</td>
<td>176</td>
<td>107</td>
<td>89</td>
<td>1</td>
<td>3.02</td>
<td></td>
<td>108</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>31.8</td>
<td>1</td>
<td>594</td>
<td>101</td>
<td>154</td>
<td>90</td>
<td>74</td>
<td>70</td>
<td>3.11</td>
<td></td>
<td>173</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>31.8</td>
<td>2</td>
<td>571</td>
<td>105</td>
<td>195</td>
<td>113</td>
<td>71</td>
<td>61</td>
<td>1.09</td>
<td>1.15</td>
<td>159</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>784</td>
<td>77</td>
<td>117</td>
<td>77</td>
<td>57</td>
<td>-1</td>
<td>2.06</td>
<td>2.11</td>
<td>67</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>881</td>
<td>68</td>
<td>118</td>
<td>77</td>
<td>42</td>
<td>26</td>
<td>2.26</td>
<td></td>
<td>81</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>698</td>
<td>86</td>
<td>123</td>
<td>77</td>
<td>41</td>
<td>25</td>
<td>0.67</td>
<td>0.71</td>
<td>79</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>0</td>
<td>703</td>
<td>85</td>
<td>130</td>
<td>81</td>
<td>70</td>
<td>-1</td>
<td>2.26</td>
<td>2.36</td>
<td>83</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>1</td>
<td>744</td>
<td>81</td>
<td>132</td>
<td>79</td>
<td>56</td>
<td>41</td>
<td>2.17</td>
<td></td>
<td>116</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>2</td>
<td>659</td>
<td>91</td>
<td>135</td>
<td>82</td>
<td>59</td>
<td>35</td>
<td>0.56</td>
<td>0.43</td>
<td>113</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
<td>27.5</td>
<td>0</td>
<td>592</td>
<td>101</td>
<td>154</td>
<td>92</td>
<td>79</td>
<td>0</td>
<td>2.99</td>
<td></td>
<td>95</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
<td>27.5</td>
<td>1</td>
<td>681</td>
<td>88</td>
<td>138</td>
<td>82</td>
<td>67</td>
<td>67</td>
<td>2.24</td>
<td></td>
<td>161</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
<td>27.5</td>
<td>2</td>
<td>747</td>
<td>80</td>
<td>134</td>
<td>76</td>
<td>70</td>
<td>58</td>
<td>1.16</td>
<td>1.08</td>
<td>154</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>916</td>
<td>66</td>
<td>130</td>
<td>79</td>
<td>57</td>
<td>37</td>
<td>0.47</td>
<td></td>
<td>113</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>785</td>
<td>76</td>
<td>146</td>
<td>89</td>
<td>55</td>
<td>35</td>
<td>-0.51</td>
<td>-0.60</td>
<td>108</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>865</td>
<td>69</td>
<td>110</td>
<td>72</td>
<td>8</td>
<td>-3</td>
<td>-0.08</td>
<td>0.02</td>
<td>8</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>899</td>
<td>67</td>
<td>102</td>
<td>66</td>
<td>9</td>
<td>-3</td>
<td>-0.28</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>
**Subject 5**

**Male**

*Height = 175 cm*

*Weight = 63 kg*

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>0</td>
<td>707</td>
<td>85</td>
<td>137</td>
<td>98</td>
<td>57</td>
<td>-1</td>
<td>-0.15</td>
<td>0.31</td>
<td>90</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>1</td>
<td>538</td>
<td>112</td>
<td>126</td>
<td>91</td>
<td>40</td>
<td>24</td>
<td>.</td>
<td>.</td>
<td>102</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>2</td>
<td>749</td>
<td>80</td>
<td>142</td>
<td>101</td>
<td>42</td>
<td>24</td>
<td>-0.73</td>
<td>-0.52</td>
<td>105</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>0</td>
<td>661</td>
<td>91</td>
<td>143</td>
<td>103</td>
<td>73</td>
<td>-1</td>
<td>2.27</td>
<td>2.56</td>
<td>115</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>1</td>
<td>651</td>
<td>92</td>
<td>137</td>
<td>99</td>
<td>52</td>
<td>39</td>
<td>.</td>
<td>.</td>
<td>146</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>2</td>
<td>750</td>
<td>80</td>
<td>149</td>
<td>106</td>
<td>51</td>
<td>42</td>
<td>0.91</td>
<td>0.83</td>
<td>148</td>
</tr>
<tr>
<td>1.4</td>
<td>0</td>
<td>37.8</td>
<td>0</td>
<td>512</td>
<td>117</td>
<td>160</td>
<td>107</td>
<td>85</td>
<td>1</td>
<td>4.45</td>
<td>.</td>
<td>137</td>
</tr>
<tr>
<td>1.4</td>
<td>0</td>
<td>37.8</td>
<td>1</td>
<td>602</td>
<td>100</td>
<td>147</td>
<td>104</td>
<td>57</td>
<td>58</td>
<td>.</td>
<td>.</td>
<td>184</td>
</tr>
<tr>
<td>1.4</td>
<td>0</td>
<td>37.8</td>
<td>2</td>
<td>689</td>
<td>87</td>
<td>169</td>
<td>122</td>
<td>65</td>
<td>64</td>
<td>2.05</td>
<td>1.98</td>
<td>205</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>871</td>
<td>69</td>
<td>111</td>
<td>75</td>
<td>23</td>
<td>-3</td>
<td>3.00</td>
<td>.</td>
<td>32</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>800</td>
<td>75</td>
<td>116</td>
<td>73</td>
<td>18</td>
<td>7</td>
<td>.</td>
<td>.</td>
<td>39</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>852</td>
<td>70</td>
<td>126</td>
<td>80</td>
<td>21</td>
<td>8</td>
<td>0.14</td>
<td>0.15</td>
<td>46</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>0</td>
<td>733</td>
<td>82</td>
<td>133</td>
<td>82</td>
<td>58</td>
<td>-2</td>
<td>2.75</td>
<td>.</td>
<td>90</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>2</td>
<td>805</td>
<td>75</td>
<td>137</td>
<td>88</td>
<td>35</td>
<td>23</td>
<td>-0.25</td>
<td>-0.21</td>
<td>92</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>0</td>
<td>687</td>
<td>87</td>
<td>142</td>
<td>92</td>
<td>72</td>
<td>-2</td>
<td>3.12</td>
<td>.</td>
<td>111</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>687</td>
<td>87</td>
<td>140</td>
<td>89</td>
<td>49</td>
<td>38</td>
<td>2.03</td>
<td>.</td>
<td>139</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>2</td>
<td>790</td>
<td>76</td>
<td>144</td>
<td>96</td>
<td>47</td>
<td>39</td>
<td>0.45</td>
<td>0.48</td>
<td>137</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>31.9</td>
<td>0</td>
<td>600</td>
<td>100</td>
<td>151</td>
<td>100</td>
<td>86</td>
<td>-1</td>
<td>2.61</td>
<td>4.66</td>
<td>135</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>31.9</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.4</td>
<td>21</td>
<td>31.9</td>
<td>2</td>
<td>735</td>
<td>82</td>
<td>145</td>
<td>96</td>
<td>62</td>
<td>57</td>
<td>1.49</td>
<td>1.56</td>
<td>191</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>766</td>
<td>78</td>
<td>108</td>
<td>71</td>
<td>44</td>
<td>-2</td>
<td>3.78</td>
<td>.</td>
<td>66</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>740</td>
<td>81</td>
<td>123</td>
<td>78</td>
<td>31</td>
<td>20</td>
<td>.</td>
<td>.</td>
<td>81</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>786</td>
<td>76</td>
<td>117</td>
<td>75</td>
<td>31</td>
<td>17</td>
<td>0.45</td>
<td>0.45</td>
<td>76</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>0</td>
<td>674</td>
<td>89</td>
<td>128</td>
<td>86</td>
<td>60</td>
<td>-2</td>
<td>3.65</td>
<td>4.38</td>
<td>92</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>1</td>
<td>685</td>
<td>88</td>
<td>130</td>
<td>86</td>
<td>39</td>
<td>30</td>
<td>.</td>
<td>.</td>
<td>110</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>2</td>
<td>773</td>
<td>78</td>
<td>132</td>
<td>87</td>
<td>44</td>
<td>27</td>
<td>0.26</td>
<td>0.37</td>
<td>114</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
<td>27.5</td>
<td>0</td>
<td>603</td>
<td>100</td>
<td>150</td>
<td>100</td>
<td>72</td>
<td>-2</td>
<td>4.62</td>
<td>.</td>
<td>112</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
<td>27.5</td>
<td>1</td>
<td>919</td>
<td>65</td>
<td>127</td>
<td>92</td>
<td>59</td>
<td>40</td>
<td>.</td>
<td>.</td>
<td>158</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
<td>27.5</td>
<td>2</td>
<td>740</td>
<td>81</td>
<td>147</td>
<td>100</td>
<td>59</td>
<td>45</td>
<td>1.26</td>
<td>1.41</td>
<td>165</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>673</td>
<td>89</td>
<td>123</td>
<td>84</td>
<td>69</td>
<td>-2</td>
<td>2.59</td>
<td>.</td>
<td>106</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>650</td>
<td>92</td>
<td>115</td>
<td>81</td>
<td>46</td>
<td>24</td>
<td>.</td>
<td>.</td>
<td>112</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>694</td>
<td>86</td>
<td>125</td>
<td>85</td>
<td>38</td>
<td>29</td>
<td>0.35</td>
<td>0.54</td>
<td>107</td>
</tr>
</tbody>
</table>
Subject 7

Female

Height = 173

Weight = 86 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.8</td>
<td>0</td>
<td>0</td>
<td>609</td>
<td>98</td>
<td>193</td>
<td>147</td>
<td>54</td>
<td>-1</td>
<td>3.45</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.8</td>
<td>1</td>
<td>695</td>
<td>86</td>
<td>192</td>
<td>138</td>
<td>43</td>
<td>43</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.8</td>
<td>2</td>
<td>692</td>
<td>87</td>
<td>196</td>
<td>141</td>
<td>44</td>
<td>45</td>
<td>1.99</td>
<td>1.96</td>
<td>103</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>0</td>
<td>580</td>
<td>103</td>
<td>193</td>
<td>159</td>
<td>62</td>
<td>0</td>
<td>4.60</td>
<td>.</td>
<td>72</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>1</td>
<td>543</td>
<td>111</td>
<td>189</td>
<td>154</td>
<td>50</td>
<td>64</td>
<td>.</td>
<td>.</td>
<td>131</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>2</td>
<td>623</td>
<td>96</td>
<td>219</td>
<td>157</td>
<td>50</td>
<td>66</td>
<td>3.29</td>
<td>3.27</td>
<td>135</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35.1</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35.1</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35.1</td>
<td>2</td>
<td>412</td>
<td>146</td>
<td>.</td>
<td>14</td>
<td>6</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>23</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>776</td>
<td>77</td>
<td>149</td>
<td>96</td>
<td>39</td>
<td>-3</td>
<td>1.79</td>
<td>.</td>
<td>42</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>818</td>
<td>73</td>
<td>139</td>
<td>92</td>
<td>26</td>
<td>14</td>
<td>0.95</td>
<td>.</td>
<td>47</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>814</td>
<td>74</td>
<td>151</td>
<td>94</td>
<td>26</td>
<td>15</td>
<td>0.35</td>
<td>0.32</td>
<td>48</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>0</td>
<td>709</td>
<td>85</td>
<td>182</td>
<td>122</td>
<td>61</td>
<td>-2</td>
<td>2.28</td>
<td>2.35</td>
<td>69</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>1</td>
<td>787</td>
<td>76</td>
<td>173</td>
<td>118</td>
<td>41</td>
<td>37</td>
<td>1.42</td>
<td>.</td>
<td>89</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>2</td>
<td>773</td>
<td>78</td>
<td>180</td>
<td>120</td>
<td>45</td>
<td>35</td>
<td>1.02</td>
<td>0.86</td>
<td>93</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>0</td>
<td>592</td>
<td>101</td>
<td>192</td>
<td>142</td>
<td>81</td>
<td>-1</td>
<td>3.23</td>
<td>3.50</td>
<td>93</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>1</td>
<td>627</td>
<td>96</td>
<td>179</td>
<td>130</td>
<td>48</td>
<td>64</td>
<td>2.24</td>
<td>.</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>2</td>
<td>664</td>
<td>90</td>
<td>202</td>
<td>140</td>
<td>58</td>
<td>55</td>
<td>1.99</td>
<td>1.98</td>
<td>132</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>0</td>
<td>535</td>
<td>112</td>
<td>193</td>
<td>151</td>
<td>88</td>
<td>-1</td>
<td>4.70</td>
<td>5.08</td>
<td>101</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>1</td>
<td>608</td>
<td>99</td>
<td>185</td>
<td>139</td>
<td>65</td>
<td>69</td>
<td>3.53</td>
<td>.</td>
<td>155</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>2</td>
<td>570</td>
<td>105</td>
<td>185</td>
<td>140</td>
<td>63</td>
<td>73</td>
<td>3.37</td>
<td>3.36</td>
<td>157</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>719</td>
<td>83</td>
<td>173</td>
<td>116</td>
<td>58</td>
<td>-3</td>
<td>1.51</td>
<td>1.50</td>
<td>65</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>807</td>
<td>74</td>
<td>167</td>
<td>110</td>
<td>37</td>
<td>25</td>
<td>0.67</td>
<td>.</td>
<td>72</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>808</td>
<td>74</td>
<td>173</td>
<td>111</td>
<td>37</td>
<td>28</td>
<td>-0.02</td>
<td>-0.14</td>
<td>75</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>0</td>
<td>640</td>
<td>94</td>
<td>187</td>
<td>134</td>
<td>78</td>
<td>-2</td>
<td>2.06</td>
<td>2.23</td>
<td>87</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>1</td>
<td>700</td>
<td>86</td>
<td>180</td>
<td>124</td>
<td>53</td>
<td>45</td>
<td>.</td>
<td>.</td>
<td>113</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>2</td>
<td>720</td>
<td>83</td>
<td>195</td>
<td>130</td>
<td>52</td>
<td>46</td>
<td>1.12</td>
<td>0.93</td>
<td>113</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>0</td>
<td>560</td>
<td>107</td>
<td>190</td>
<td>144</td>
<td>90</td>
<td>-2</td>
<td>3.00</td>
<td>.</td>
<td>102</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>1</td>
<td>634</td>
<td>95</td>
<td>181</td>
<td>131</td>
<td>61</td>
<td>59</td>
<td>.</td>
<td>.</td>
<td>140</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>2</td>
<td>650</td>
<td>92</td>
<td>187</td>
<td>136</td>
<td>59</td>
<td>62</td>
<td>2.04</td>
<td>2.14</td>
<td>140</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>613</td>
<td>98</td>
<td>141</td>
<td>98</td>
<td>69</td>
<td>-2</td>
<td>2.30</td>
<td>.</td>
<td>78</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>660</td>
<td>91</td>
<td>132</td>
<td>95</td>
<td>48</td>
<td>41</td>
<td>-1.45</td>
<td>.</td>
<td>103</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>680</td>
<td>88</td>
<td>152</td>
<td>100</td>
<td>43</td>
<td>41</td>
<td>-1.41</td>
<td>-1.40</td>
<td>98</td>
</tr>
</tbody>
</table>
Subject 8

Female

Height = 176 cm

Weight = 64 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>0.95</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>16</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>128</td>
<td>94</td>
<td>8</td>
<td>-1</td>
<td>0.41</td>
<td>0.44</td>
<td>10</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>0</td>
<td>750</td>
<td>80</td>
<td>97</td>
<td>68</td>
<td>65</td>
<td>-1</td>
<td>0.85</td>
<td>1.04</td>
<td>101</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>35</td>
<td>28</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>98</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>2</td>
<td>964</td>
<td>62</td>
<td>63</td>
<td>55</td>
<td>38</td>
<td>33</td>
<td>0.03</td>
<td>0.08</td>
<td>112</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>0</td>
<td>694</td>
<td>86</td>
<td>96</td>
<td>65</td>
<td>82</td>
<td>1</td>
<td>2.50</td>
<td>.</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>2</td>
<td>910</td>
<td>66</td>
<td>87</td>
<td>77</td>
<td>51</td>
<td>53</td>
<td>0.91</td>
<td>0.94</td>
<td>163</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>0</td>
<td>712</td>
<td>84</td>
<td>123</td>
<td>87</td>
<td>90</td>
<td>1</td>
<td>4.14</td>
<td>4.65</td>
<td>143</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>1</td>
<td>505</td>
<td>119</td>
<td>124</td>
<td>117</td>
<td>57</td>
<td>63</td>
<td>4.30</td>
<td>.</td>
<td>188</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>2</td>
<td>818</td>
<td>73</td>
<td>118</td>
<td>109</td>
<td>59</td>
<td>63</td>
<td>1.74</td>
<td>1.96</td>
<td>191</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>885</td>
<td>68</td>
<td>141</td>
<td>84</td>
<td>29</td>
<td>-3</td>
<td>0.84</td>
<td>0.82</td>
<td>41</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>1</td>
<td>0</td>
<td>949</td>
<td>63</td>
<td>144</td>
<td>77</td>
<td>19</td>
<td>8</td>
<td>1.29</td>
<td>.</td>
<td>42</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>809</td>
<td>74</td>
<td>139</td>
<td>84</td>
<td>22</td>
<td>8</td>
<td>-0.35</td>
<td>-0.41</td>
<td>47</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>0</td>
<td>791</td>
<td>76</td>
<td>166</td>
<td>109</td>
<td>53</td>
<td>-1</td>
<td>0.54</td>
<td>0.62</td>
<td>80</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>1</td>
<td>848</td>
<td>71</td>
<td>157</td>
<td>101</td>
<td>30</td>
<td>22</td>
<td>.</td>
<td>.</td>
<td>82</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>2</td>
<td>722</td>
<td>83</td>
<td>166</td>
<td>108</td>
<td>35</td>
<td>24</td>
<td>-0.92</td>
<td>-0.92</td>
<td>93</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>0</td>
<td>667</td>
<td>90</td>
<td>188</td>
<td>142</td>
<td>63</td>
<td>0</td>
<td>0.77</td>
<td>0.93</td>
<td>98</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>772</td>
<td>78</td>
<td>183</td>
<td>126</td>
<td>44</td>
<td>41</td>
<td>.</td>
<td>.</td>
<td>133</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>2</td>
<td>635</td>
<td>95</td>
<td>190</td>
<td>137</td>
<td>45</td>
<td>42</td>
<td>-0.26</td>
<td>-0.11</td>
<td>135</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>0</td>
<td>617</td>
<td>97</td>
<td>191</td>
<td>156</td>
<td>69</td>
<td>-1</td>
<td>2.38</td>
<td>3.09</td>
<td>106</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>1</td>
<td>640</td>
<td>94</td>
<td>191</td>
<td>145</td>
<td>43</td>
<td>53</td>
<td>3.23</td>
<td>.</td>
<td>151</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>2</td>
<td>779</td>
<td>77</td>
<td>207</td>
<td>150</td>
<td>47</td>
<td>55</td>
<td>0.62</td>
<td>0.73</td>
<td>160</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>830</td>
<td>72</td>
<td>140</td>
<td>90</td>
<td>45</td>
<td>-3</td>
<td>0.01</td>
<td>.</td>
<td>67</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>902</td>
<td>67</td>
<td>145</td>
<td>83</td>
<td>30</td>
<td>19</td>
<td>.</td>
<td>.</td>
<td>76</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>662</td>
<td>91</td>
<td>152</td>
<td>94</td>
<td>27</td>
<td>15</td>
<td>0.35</td>
<td>0.13</td>
<td>66</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>0</td>
<td>745</td>
<td>81</td>
<td>167</td>
<td>113</td>
<td>54</td>
<td>-2</td>
<td>0.45</td>
<td>0.71</td>
<td>82</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>1</td>
<td>777</td>
<td>77</td>
<td>171</td>
<td>112</td>
<td>39</td>
<td>33</td>
<td>1.05</td>
<td>.</td>
<td>112</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>2</td>
<td>1138</td>
<td>53</td>
<td>161</td>
<td>112</td>
<td>32</td>
<td>28</td>
<td>0.36</td>
<td>0.25</td>
<td>93</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>0</td>
<td>746</td>
<td>80</td>
<td>177</td>
<td>130</td>
<td>57</td>
<td>-2</td>
<td>1.74</td>
<td>2.21</td>
<td>87</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>1</td>
<td>738</td>
<td>81</td>
<td>177</td>
<td>124</td>
<td>43</td>
<td>46</td>
<td>1.45</td>
<td>.</td>
<td>139</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>2</td>
<td>894</td>
<td>67</td>
<td>184</td>
<td>130</td>
<td>35</td>
<td>47</td>
<td>-0.81</td>
<td>-0.55</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>733</td>
<td>82</td>
<td>181</td>
<td>129</td>
<td>73</td>
<td>-2</td>
<td>0.05</td>
<td>.</td>
<td>110</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>827</td>
<td>73</td>
<td>178</td>
<td>117</td>
<td>41</td>
<td>35</td>
<td>.</td>
<td>.</td>
<td>119</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>702</td>
<td>85</td>
<td>192</td>
<td>122</td>
<td>37</td>
<td>34</td>
<td>-1.32</td>
<td>-1.42</td>
<td>110</td>
</tr>
</tbody>
</table>
## Subject 10

**Male**

**Height = 174**

**Weight unknown**

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1029</td>
<td>58</td>
<td>142</td>
<td>90</td>
<td>10</td>
<td>-2</td>
<td>0.58</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>941</td>
<td>64</td>
<td>140</td>
<td>90</td>
<td>12</td>
<td>1</td>
<td>0.28</td>
<td>0.33</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>0</td>
<td>696</td>
<td>86</td>
<td>159</td>
<td>112</td>
<td>64</td>
<td>-1</td>
<td>3.66</td>
<td>4.49</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>1</td>
<td>745</td>
<td>81</td>
<td>157</td>
<td>107</td>
<td>49</td>
<td>30</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>2</td>
<td>849</td>
<td>71</td>
<td>157</td>
<td>109</td>
<td>47</td>
<td>32</td>
<td>1.10</td>
<td>0.98</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>0</td>
<td>658</td>
<td>91</td>
<td>166</td>
<td>116</td>
<td>69</td>
<td>-1</td>
<td>5.72</td>
<td>6.29</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>2</td>
<td>704</td>
<td>85</td>
<td>172</td>
<td>117</td>
<td>61</td>
<td>51</td>
<td>2.23</td>
<td>2.28</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35</td>
<td>0</td>
<td>599</td>
<td>100</td>
<td>162</td>
<td>118</td>
<td>86</td>
<td>0</td>
<td>7.43</td>
<td>8.36</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35</td>
<td>1</td>
<td>599</td>
<td>100</td>
<td>161</td>
<td>116</td>
<td>67</td>
<td>61</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35</td>
<td>2</td>
<td>669</td>
<td>90</td>
<td>172</td>
<td>119</td>
<td>69</td>
<td>63</td>
<td>3.69</td>
<td>3.56</td>
<td>.</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>904</td>
<td>66</td>
<td>129</td>
<td>76</td>
<td>31</td>
<td>-3</td>
<td>2.93</td>
<td>2.82</td>
<td>.</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>1036</td>
<td>58</td>
<td>124</td>
<td>77</td>
<td>20</td>
<td>7</td>
<td>2.65</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>888</td>
<td>68</td>
<td>142</td>
<td>84</td>
<td>20</td>
<td>9</td>
<td>1.11</td>
<td>0.74</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>0</td>
<td>725</td>
<td>83</td>
<td>140</td>
<td>91</td>
<td>56</td>
<td>-2</td>
<td>3.79</td>
<td>4.13</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>1</td>
<td>857</td>
<td>70</td>
<td>143</td>
<td>89</td>
<td>40</td>
<td>22</td>
<td>2.43</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>2</td>
<td>849</td>
<td>71</td>
<td>151</td>
<td>99</td>
<td>40</td>
<td>25</td>
<td>0.03</td>
<td>0.28</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>0</td>
<td>707</td>
<td>85</td>
<td>155</td>
<td>107</td>
<td>72</td>
<td>-2</td>
<td>4.45</td>
<td>4.69</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>1</td>
<td>728</td>
<td>82</td>
<td>142</td>
<td>100</td>
<td>53</td>
<td>40</td>
<td>3.70</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>2</td>
<td>765</td>
<td>78</td>
<td>159</td>
<td>108</td>
<td>55</td>
<td>41</td>
<td>1.30</td>
<td>1.27</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>0</td>
<td>593</td>
<td>101</td>
<td>154</td>
<td>112</td>
<td>77</td>
<td>-1</td>
<td>6.60</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>1</td>
<td>633</td>
<td>95</td>
<td>154</td>
<td>109</td>
<td>57</td>
<td>55</td>
<td>3.07</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>2</td>
<td>686</td>
<td>87</td>
<td>167</td>
<td>118</td>
<td>61</td>
<td>54</td>
<td>2.11</td>
<td>2.21</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>879</td>
<td>68</td>
<td>149</td>
<td>99</td>
<td>51</td>
<td>-3</td>
<td>1.91</td>
<td>1.94</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>872</td>
<td>69</td>
<td>139</td>
<td>92</td>
<td>37</td>
<td>16</td>
<td>0.48</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>892</td>
<td>67</td>
<td>163</td>
<td>107</td>
<td>38</td>
<td>19</td>
<td>-0.44</td>
<td>-0.56</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>0</td>
<td>717</td>
<td>84</td>
<td>173</td>
<td>123</td>
<td>74</td>
<td>-2</td>
<td>3.29</td>
<td>4.26</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>1</td>
<td>718</td>
<td>84</td>
<td>186</td>
<td>124</td>
<td>46</td>
<td>37</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>2</td>
<td>893</td>
<td>67</td>
<td>176</td>
<td>123</td>
<td>46</td>
<td>35</td>
<td>-0.27</td>
<td>-0.26</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>0</td>
<td>638</td>
<td>94</td>
<td>173</td>
<td>127</td>
<td>85</td>
<td>-2</td>
<td>4.04</td>
<td>5.52</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>1</td>
<td>637</td>
<td>94</td>
<td>174</td>
<td>121</td>
<td>54</td>
<td>46</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>2</td>
<td>934</td>
<td>64</td>
<td>179</td>
<td>129</td>
<td>56</td>
<td>43</td>
<td>0.63</td>
<td>1.02</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>800</td>
<td>75</td>
<td>128</td>
<td>86</td>
<td>85</td>
<td>-2</td>
<td>3.24</td>
<td>3.22</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>807</td>
<td>74</td>
<td>129</td>
<td>81</td>
<td>50</td>
<td>35</td>
<td>0.64</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>858</td>
<td>70</td>
<td>140</td>
<td>88</td>
<td>51</td>
<td>32</td>
<td>-0.24</td>
<td>-0.21</td>
<td>.</td>
</tr>
</tbody>
</table>
Subject 11

Male

Height = 187 cm

Weight = 91 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>641</td>
<td>94</td>
<td>135</td>
<td>67</td>
<td>12</td>
<td>4</td>
<td>1.27</td>
<td>.</td>
<td>18</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>753</td>
<td>80</td>
<td>138</td>
<td>68</td>
<td>10</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>13</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>771</td>
<td>78</td>
<td>142</td>
<td>68</td>
<td>17</td>
<td>6</td>
<td>0.17</td>
<td>-0.20</td>
<td>25</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.3</td>
<td>0</td>
<td>606</td>
<td>99</td>
<td>135</td>
<td>78</td>
<td>76</td>
<td>-1</td>
<td>3.53</td>
<td>3.91</td>
<td>83</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.3</td>
<td>1</td>
<td>672</td>
<td>89</td>
<td>123</td>
<td>72</td>
<td>58</td>
<td>35</td>
<td>2.20</td>
<td>.</td>
<td>104</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.3</td>
<td>2</td>
<td>717</td>
<td>84</td>
<td>149</td>
<td>75</td>
<td>50</td>
<td>39</td>
<td>0.57</td>
<td>0.48</td>
<td>98</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.5</td>
<td>0</td>
<td>527</td>
<td>114</td>
<td>129</td>
<td>79</td>
<td>85</td>
<td>0</td>
<td>4.91</td>
<td>5.34</td>
<td>94</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.5</td>
<td>1</td>
<td>565</td>
<td>106</td>
<td>116</td>
<td>69</td>
<td>72</td>
<td>59</td>
<td>3.38</td>
<td>.</td>
<td>145</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.5</td>
<td>2</td>
<td>677</td>
<td>89</td>
<td>142</td>
<td>74</td>
<td>55</td>
<td>57</td>
<td>1.05</td>
<td>1.08</td>
<td>124</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.5</td>
<td>0</td>
<td>458</td>
<td>131</td>
<td>118</td>
<td>75</td>
<td>98</td>
<td>0</td>
<td>6.48</td>
<td>7.06</td>
<td>108</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.5</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>91</td>
<td>58</td>
<td>81</td>
<td>78</td>
<td>.</td>
<td>.</td>
<td>175</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.5</td>
<td>2</td>
<td>542</td>
<td>111</td>
<td>132</td>
<td>74</td>
<td>77</td>
<td>77</td>
<td>2.77</td>
<td>2.62</td>
<td>170</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>774</td>
<td>77</td>
<td>166</td>
<td>64</td>
<td>34</td>
<td>-3</td>
<td>1.50</td>
<td>1.63</td>
<td>34</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>904</td>
<td>66</td>
<td>173</td>
<td>51</td>
<td>21</td>
<td>15</td>
<td>.</td>
<td>.</td>
<td>40</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>27</td>
<td>14</td>
<td>-0.33</td>
<td>-0.55</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>0</td>
<td>736</td>
<td>82</td>
<td>137</td>
<td>50</td>
<td>77</td>
<td>-2</td>
<td>2.25</td>
<td>2.54</td>
<td>83</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>1</td>
<td>741</td>
<td>81</td>
<td>178</td>
<td>51</td>
<td>55</td>
<td>28</td>
<td>1.25</td>
<td>.</td>
<td>91</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>48</td>
<td>31</td>
<td>-0.39</td>
<td>-0.51</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.7</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>86</td>
<td>-1</td>
<td>3.05</td>
<td>3.61</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.7</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>66</td>
<td>54</td>
<td>1.33</td>
<td>.</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.7</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>57</td>
<td>52</td>
<td>-0.51</td>
<td>-0.43</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.3</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>90</td>
<td>-1</td>
<td>4.72</td>
<td>5.05</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.3</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>71</td>
<td>69</td>
<td>2.17</td>
<td>.</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.3</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>59</td>
<td>66</td>
<td>0.48</td>
<td>0.47</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>676</td>
<td>89</td>
<td>151</td>
<td>71</td>
<td>69</td>
<td>-3</td>
<td>1.60</td>
<td>1.74</td>
<td>73</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>839</td>
<td>71</td>
<td>148</td>
<td>70</td>
<td>42</td>
<td>33</td>
<td>0.58</td>
<td>.</td>
<td>83</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>697</td>
<td>86</td>
<td>148</td>
<td>71</td>
<td>42</td>
<td>29</td>
<td>-0.94</td>
<td>-1.03</td>
<td>78</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.7</td>
<td>0</td>
<td>649</td>
<td>93</td>
<td>144</td>
<td>80</td>
<td>81</td>
<td>-2</td>
<td>2.40</td>
<td>2.87</td>
<td>87</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.7</td>
<td>1</td>
<td>760</td>
<td>79</td>
<td>139</td>
<td>68</td>
<td>62</td>
<td>47</td>
<td>0.75</td>
<td>.</td>
<td>120</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.7</td>
<td>2</td>
<td>740</td>
<td>81</td>
<td>144</td>
<td>73</td>
<td>52</td>
<td>50</td>
<td>-1.23</td>
<td>-1.17</td>
<td>112</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>0</td>
<td>588</td>
<td>102</td>
<td>143</td>
<td>82</td>
<td>89</td>
<td>-1</td>
<td>4.08</td>
<td>4.55</td>
<td>96</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>1</td>
<td>720</td>
<td>83</td>
<td>142</td>
<td>73</td>
<td>69</td>
<td>55</td>
<td>0.65</td>
<td>.</td>
<td>137</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>2</td>
<td>669</td>
<td>90</td>
<td>153</td>
<td>82</td>
<td>62</td>
<td>51</td>
<td>-0.27</td>
<td>-0.39</td>
<td>125</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>651</td>
<td>92</td>
<td>151</td>
<td>85</td>
<td>92</td>
<td>-2</td>
<td>2.57</td>
<td>2.95</td>
<td>99</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>754</td>
<td>80</td>
<td>146</td>
<td>78</td>
<td>58</td>
<td>47</td>
<td>-0.17</td>
<td>.</td>
<td>116</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>824</td>
<td>73</td>
<td>161</td>
<td>85</td>
<td>60</td>
<td>38</td>
<td>1.06</td>
<td>0.17</td>
<td>108</td>
</tr>
</tbody>
</table>
Subject 12

Male

Height = 177 cm

Weight = 86 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>885</td>
<td>68</td>
<td>105</td>
<td>69</td>
<td>11</td>
<td>0</td>
<td>0.48</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>752</td>
<td>80</td>
<td>105</td>
<td>65</td>
<td>16</td>
<td>5</td>
<td>0.29</td>
<td>0.19</td>
<td>24</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>0</td>
<td>671</td>
<td>89</td>
<td>124</td>
<td>78</td>
<td>55</td>
<td>-2</td>
<td>1.32</td>
<td>1.86</td>
<td>62</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>1</td>
<td>736</td>
<td>82</td>
<td>130</td>
<td>80</td>
<td>44</td>
<td>32</td>
<td></td>
<td></td>
<td>89</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>2</td>
<td>815</td>
<td>74</td>
<td>143</td>
<td>85</td>
<td>39</td>
<td>35</td>
<td>0.96</td>
<td>0.82</td>
<td>86</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td></td>
<td>661</td>
<td>91</td>
<td>139</td>
<td>93</td>
<td>65</td>
<td>-1</td>
<td>2.63</td>
<td>2.87</td>
<td>76</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>1</td>
<td>661</td>
<td>91</td>
<td>140</td>
<td>92</td>
<td>57</td>
<td>58</td>
<td>1.10</td>
<td></td>
<td>134</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>2</td>
<td>682</td>
<td>88</td>
<td>169</td>
<td>109</td>
<td>48</td>
<td>46</td>
<td>2.13</td>
<td>1.64</td>
<td>110</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>37.7</td>
<td>0</td>
<td>603</td>
<td>100</td>
<td>158</td>
<td>103</td>
<td>71</td>
<td>0</td>
<td>2.80</td>
<td>3.34</td>
<td>84</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>37.7</td>
<td>1</td>
<td>558</td>
<td>108</td>
<td>143</td>
<td>94</td>
<td>61</td>
<td>74</td>
<td>2.25</td>
<td></td>
<td>157</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>37.7</td>
<td>2</td>
<td>760</td>
<td>79</td>
<td>178</td>
<td>111</td>
<td>51</td>
<td>48</td>
<td>2.65</td>
<td>2.67</td>
<td>116</td>
</tr>
<tr>
<td>0.36</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>828</td>
<td>72</td>
<td>112</td>
<td>71</td>
<td>26</td>
<td>-3</td>
<td>1.88</td>
<td>2.09</td>
</tr>
<tr>
<td>0.36</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>860</td>
<td>68</td>
<td>101</td>
<td>66</td>
<td>23</td>
<td>10</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>736</td>
<td>82</td>
<td>118</td>
<td>68</td>
<td>25</td>
<td>13</td>
<td>0.63</td>
<td>0.71</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>21</td>
<td>18.2</td>
<td>0</td>
<td>773</td>
<td>78</td>
<td>123</td>
<td>76</td>
<td>59</td>
<td>-3</td>
<td>2.31</td>
<td>2.59</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>21</td>
<td>18.2</td>
<td>1</td>
<td>783</td>
<td>77</td>
<td>126</td>
<td>73</td>
<td>41</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>21</td>
<td>18.2</td>
<td>2</td>
<td>739</td>
<td>81</td>
<td>136</td>
<td>80</td>
<td>35</td>
<td>27</td>
<td>1.12</td>
<td>1.39</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>21</td>
<td>25</td>
<td>0</td>
<td>671</td>
<td>89</td>
<td>137</td>
<td>85</td>
<td>75</td>
<td>-2</td>
<td>2.17</td>
<td>2.64</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>618</td>
<td>97</td>
<td>130</td>
<td>83</td>
<td>59</td>
<td>52</td>
<td>-0.31</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>21</td>
<td>25</td>
<td>2</td>
<td>719</td>
<td>83</td>
<td>148</td>
<td>92</td>
<td>43</td>
<td>41</td>
<td>2.14</td>
<td>1.96</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>21</td>
<td>28.6</td>
<td>0</td>
<td>620</td>
<td>97</td>
<td>152</td>
<td>97</td>
<td>82</td>
<td>-1</td>
<td>3.21</td>
<td>3.64</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>21</td>
<td>28.6</td>
<td>1</td>
<td>599</td>
<td>100</td>
<td>139</td>
<td>87</td>
<td>66</td>
<td>63</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>21</td>
<td>28.6</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47</td>
<td>42</td>
<td>2.66</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>762</td>
<td>79</td>
<td>109</td>
<td>65</td>
<td>58</td>
<td>-3</td>
<td>1.71</td>
<td>1.97</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>747</td>
<td>80</td>
<td>112</td>
<td>61</td>
<td>36</td>
<td>30</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>800</td>
<td>75</td>
<td>118</td>
<td>66</td>
<td>36</td>
<td>23</td>
<td>-0.32</td>
<td>0.09</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>45</td>
<td>17.8</td>
<td>0</td>
<td>701</td>
<td>86</td>
<td>134</td>
<td>81</td>
<td>65</td>
<td>-2</td>
<td>1.15</td>
<td>1.62</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>45</td>
<td>17.8</td>
<td>1</td>
<td>707</td>
<td>85</td>
<td>131</td>
<td>76</td>
<td>56</td>
<td>43</td>
<td>-1.13</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>45</td>
<td>17.8</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>41</td>
<td>30</td>
<td>1.38</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>45</td>
<td>23.2</td>
<td>0</td>
<td>675</td>
<td>89</td>
<td>141</td>
<td>88</td>
<td>71</td>
<td>-2</td>
<td>1.87</td>
<td>2.42</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>45</td>
<td>23.2</td>
<td>1</td>
<td>699</td>
<td>86</td>
<td>131</td>
<td>81</td>
<td>57</td>
<td>56</td>
<td>-0.49</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>45</td>
<td>23.2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
<td>39</td>
<td>2.30</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>90</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>90</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>
Subject 13
Female
Height = 176 cm
Weight = 71 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.7</td>
<td>0</td>
<td>2</td>
<td>739</td>
<td>81</td>
<td>88</td>
<td>57</td>
<td>11</td>
<td>-1</td>
<td>0.7</td>
<td>0.7</td>
<td>-1.87</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>0</td>
<td>617</td>
<td>97</td>
<td>119</td>
<td>81</td>
<td>69</td>
<td>-1</td>
<td>4.10</td>
<td>0.34</td>
<td>-0.06</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>1</td>
<td>678</td>
<td>89</td>
<td>118</td>
<td>79</td>
<td>42</td>
<td>38</td>
<td>114</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1022</td>
<td>59</td>
<td>121</td>
<td>76</td>
<td>10</td>
<td>-1</td>
<td>12</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.9</td>
<td>1</td>
<td>588</td>
<td>102</td>
<td>114</td>
<td>78</td>
<td>53</td>
<td>51</td>
<td>146</td>
<td>0.7</td>
<td>-1</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>2</td>
<td>829</td>
<td>72</td>
<td>123</td>
<td>78</td>
<td>41</td>
<td>37</td>
<td>110</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>34.9</td>
<td>0</td>
<td>571</td>
<td>105</td>
<td>128</td>
<td>85</td>
<td>78</td>
<td>2</td>
<td>113</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>1</td>
<td>579</td>
<td>104</td>
<td>119</td>
<td>81</td>
<td>55</td>
<td>62</td>
<td>165</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>1041</td>
<td>58</td>
<td>115</td>
<td>72</td>
<td>27</td>
<td>-3</td>
<td>34</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>1040</td>
<td>58</td>
<td>116</td>
<td>69</td>
<td>19</td>
<td>12</td>
<td>43</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>0</td>
<td>816</td>
<td>74</td>
<td>121</td>
<td>79</td>
<td>49</td>
<td>-3</td>
<td>66</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>1</td>
<td>847</td>
<td>71</td>
<td>121</td>
<td>79</td>
<td>36</td>
<td>27</td>
<td>89</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>2</td>
<td>804</td>
<td>75</td>
<td>123</td>
<td>78</td>
<td>36</td>
<td>24</td>
<td>84</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>0</td>
<td>718</td>
<td>84</td>
<td>126</td>
<td>82</td>
<td>66</td>
<td>-2</td>
<td>91</td>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>717</td>
<td>84</td>
<td>122</td>
<td>80</td>
<td>47</td>
<td>43</td>
<td>128</td>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>2</td>
<td>871</td>
<td>69</td>
<td>126</td>
<td>82</td>
<td>43</td>
<td>38</td>
<td>115</td>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>0</td>
<td>626</td>
<td>96</td>
<td>123</td>
<td>79</td>
<td>69</td>
<td>-1</td>
<td>96</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>1</td>
<td>591</td>
<td>102</td>
<td>119</td>
<td>78</td>
<td>57</td>
<td>56</td>
<td>160</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>2</td>
<td>755</td>
<td>79</td>
<td>123</td>
<td>84</td>
<td>45</td>
<td>48</td>
<td>131</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>801</td>
<td>75</td>
<td>106</td>
<td>61</td>
<td>48</td>
<td>-3</td>
<td>63</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>866</td>
<td>69</td>
<td>100</td>
<td>56</td>
<td>31</td>
<td>23</td>
<td>76</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>774</td>
<td>78</td>
<td>117</td>
<td>59</td>
<td>34</td>
<td>20</td>
<td>76</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>0</td>
<td>727</td>
<td>83</td>
<td>118</td>
<td>67</td>
<td>55</td>
<td>-2</td>
<td>75</td>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>1</td>
<td>746</td>
<td>80</td>
<td>114</td>
<td>66</td>
<td>44</td>
<td>35</td>
<td>111</td>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>2</td>
<td>810</td>
<td>74</td>
<td>118</td>
<td>70</td>
<td>42</td>
<td>31</td>
<td>103</td>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>0</td>
<td>632</td>
<td>95</td>
<td>118</td>
<td>73</td>
<td>72</td>
<td>-2</td>
<td>99</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>1</td>
<td>587</td>
<td>102</td>
<td>109</td>
<td>69</td>
<td>55</td>
<td>46</td>
<td>144</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>694</td>
<td>86</td>
<td>97</td>
<td>61</td>
<td>82</td>
<td>-2</td>
<td>116</td>
<td>1</td>
<td>1.49</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>737</td>
<td>81</td>
<td>100</td>
<td>61</td>
<td>50</td>
<td>35</td>
<td>120</td>
<td>1</td>
<td>1.49</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>770</td>
<td>78</td>
<td>107</td>
<td>61</td>
<td>48</td>
<td>32</td>
<td>114</td>
<td>1</td>
<td>1.49</td>
</tr>
</tbody>
</table>
Subject 14

Male

Height = 188 cm

Weight = 92 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>778</td>
<td>77</td>
<td>104</td>
<td>57</td>
<td>13</td>
<td>1</td>
<td>0.84</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>736</td>
<td>82</td>
<td>120</td>
<td>65</td>
<td>20</td>
<td>6</td>
<td>-0.55</td>
<td>-0.30</td>
<td>28</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.3</td>
<td>0</td>
<td>643</td>
<td>93</td>
<td>108</td>
<td>60</td>
<td>73</td>
<td>0</td>
<td>2.93</td>
<td>3.08</td>
<td>79</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.3</td>
<td>1</td>
<td>680</td>
<td>88</td>
<td>103</td>
<td>55</td>
<td>50</td>
<td>41</td>
<td>1.80</td>
<td>.</td>
<td>99</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.3</td>
<td>2</td>
<td>691</td>
<td>87</td>
<td>113</td>
<td>61</td>
<td>57</td>
<td>29</td>
<td>1.07</td>
<td>0.99</td>
<td>94</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.4</td>
<td>0</td>
<td>641</td>
<td>94</td>
<td>111</td>
<td>62</td>
<td>75</td>
<td>0</td>
<td>4.10</td>
<td>4.35</td>
<td>81</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.4</td>
<td>1</td>
<td>598</td>
<td>100</td>
<td>108</td>
<td>61</td>
<td>53</td>
<td>62</td>
<td>2.87</td>
<td>.</td>
<td>124</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.4</td>
<td>2</td>
<td>680</td>
<td>88</td>
<td>125</td>
<td>64</td>
<td>71</td>
<td>41</td>
<td>1.92</td>
<td>1.91</td>
<td>122</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.4</td>
<td>0</td>
<td>650</td>
<td>92</td>
<td>126</td>
<td>67</td>
<td>86</td>
<td>1</td>
<td>5.60</td>
<td>5.99</td>
<td>95</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.4</td>
<td>1</td>
<td>669</td>
<td>90</td>
<td>118</td>
<td>64</td>
<td>69</td>
<td>65</td>
<td>3.17</td>
<td>.</td>
<td>146</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.4</td>
<td>2</td>
<td>633</td>
<td>95</td>
<td>138</td>
<td>69</td>
<td>79</td>
<td>50</td>
<td>2.80</td>
<td>3.02</td>
<td>140</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>740</td>
<td>81</td>
<td>110</td>
<td>60</td>
<td>45</td>
<td>-3</td>
<td>1.42</td>
<td>1.47</td>
<td>45</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>779</td>
<td>77</td>
<td>97</td>
<td>55</td>
<td>32</td>
<td>15</td>
<td>1.10</td>
<td>.</td>
<td>51</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>714</td>
<td>84</td>
<td>120</td>
<td>62</td>
<td>32</td>
<td>13</td>
<td>-0.48</td>
<td>-0.42</td>
<td>48</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18</td>
<td>0</td>
<td>695</td>
<td>86</td>
<td>125</td>
<td>65</td>
<td>77</td>
<td>-2</td>
<td>1.91</td>
<td>2.00</td>
<td>82</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18</td>
<td>1</td>
<td>704</td>
<td>85</td>
<td>109</td>
<td>60</td>
<td>54</td>
<td>32</td>
<td>0.70</td>
<td>.</td>
<td>92</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18</td>
<td>2</td>
<td>752</td>
<td>80</td>
<td>131</td>
<td>66</td>
<td>55</td>
<td>24</td>
<td>-0.11</td>
<td>0.07</td>
<td>86</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.7</td>
<td>0</td>
<td>659</td>
<td>91</td>
<td>123</td>
<td>67</td>
<td>80</td>
<td>-1</td>
<td>2.34</td>
<td>2.70</td>
<td>86</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.7</td>
<td>1</td>
<td>711</td>
<td>84</td>
<td>108</td>
<td>62</td>
<td>60</td>
<td>54</td>
<td>1.41</td>
<td>.</td>
<td>123</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.7</td>
<td>2</td>
<td>743</td>
<td>81</td>
<td>128</td>
<td>67</td>
<td>78</td>
<td>36</td>
<td>1.02</td>
<td>0.71</td>
<td>124</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.3</td>
<td>0</td>
<td>644</td>
<td>93</td>
<td>124</td>
<td>67</td>
<td>81</td>
<td>0</td>
<td>2.40</td>
<td>3.45</td>
<td>88</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.3</td>
<td>1</td>
<td>621</td>
<td>97</td>
<td>104</td>
<td>62</td>
<td>64</td>
<td>67</td>
<td>1.91</td>
<td>.</td>
<td>142</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.3</td>
<td>2</td>
<td>993</td>
<td>60</td>
<td>101</td>
<td>56</td>
<td>92</td>
<td>33</td>
<td>1.79</td>
<td>1.88</td>
<td>135</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>706</td>
<td>85</td>
<td>115</td>
<td>64</td>
<td>58</td>
<td>-3</td>
<td>1.07</td>
<td>1.15</td>
<td>59</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>718</td>
<td>84</td>
<td>120</td>
<td>64</td>
<td>41</td>
<td>30</td>
<td>-0.13</td>
<td>.</td>
<td>77</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>687</td>
<td>87</td>
<td>134</td>
<td>66</td>
<td>49</td>
<td>24</td>
<td>-1.33</td>
<td>-1.26</td>
<td>80</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.7</td>
<td>0</td>
<td>675</td>
<td>89</td>
<td>129</td>
<td>71</td>
<td>77</td>
<td>-2</td>
<td>1.21</td>
<td>1.55</td>
<td>81</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.7</td>
<td>1</td>
<td>699</td>
<td>86</td>
<td>116</td>
<td>68</td>
<td>57</td>
<td>48</td>
<td>0.43</td>
<td>.</td>
<td>114</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.7</td>
<td>2</td>
<td>692</td>
<td>87</td>
<td>.</td>
<td>56</td>
<td>30</td>
<td>-0.22</td>
<td>-0.35</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>0</td>
<td>647</td>
<td>93</td>
<td>125</td>
<td>69</td>
<td>90</td>
<td>-1</td>
<td>1.47</td>
<td>1.82</td>
<td>95</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>1</td>
<td>610</td>
<td>98</td>
<td>112</td>
<td>68</td>
<td>73</td>
<td>51</td>
<td>1.03</td>
<td>.</td>
<td>134</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>69</td>
<td>27</td>
<td>0.65</td>
<td>0.83</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>663</td>
<td>90</td>
<td>135</td>
<td>79</td>
<td>72</td>
<td>-3</td>
<td>2.31</td>
<td>2.50</td>
<td>75</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>665</td>
<td>90</td>
<td>.</td>
<td>53</td>
<td>40</td>
<td>.</td>
<td>.</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>733</td>
<td>82</td>
<td>144</td>
<td>79</td>
<td>59</td>
<td>43</td>
<td>-0.15</td>
<td>-0.14</td>
<td>110</td>
</tr>
</tbody>
</table>
Subject 15
Male
Height = 167 cm
Weight = 60 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>983</td>
<td>61</td>
<td>109</td>
<td>69</td>
<td>11</td>
<td>-3</td>
<td>0.32</td>
<td>.</td>
<td>12</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1028</td>
<td>58</td>
<td>109</td>
<td>69</td>
<td>10</td>
<td>-2</td>
<td>0.88</td>
<td>.</td>
<td>13</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>986</td>
<td>61</td>
<td>114</td>
<td>75</td>
<td>14</td>
<td>5</td>
<td>-1.96</td>
<td>-1.82</td>
<td>31</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>27</td>
<td>0</td>
<td>738</td>
<td>81</td>
<td>123</td>
<td>72</td>
<td>59</td>
<td>-1</td>
<td>1.58</td>
<td>2.36</td>
<td>97</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>27</td>
<td>1</td>
<td>772</td>
<td>78</td>
<td>123</td>
<td>72</td>
<td>38</td>
<td>20</td>
<td>3.29</td>
<td>.</td>
<td>98</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>27</td>
<td>2</td>
<td>599</td>
<td>100</td>
<td>125</td>
<td>75</td>
<td>38</td>
<td>31</td>
<td>-2.02</td>
<td>-1.96</td>
<td>116</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32.2</td>
<td>0</td>
<td>690</td>
<td>87</td>
<td>121</td>
<td>79</td>
<td>61</td>
<td>0</td>
<td>3.86</td>
<td>4.45</td>
<td>102</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32.2</td>
<td>1</td>
<td>801</td>
<td>75</td>
<td>117</td>
<td>72</td>
<td>49</td>
<td>37</td>
<td>0.98</td>
<td>.</td>
<td>145</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32.2</td>
<td>2</td>
<td>726</td>
<td>83</td>
<td>129</td>
<td>82</td>
<td>48</td>
<td>43</td>
<td>-1.10</td>
<td>-1.40</td>
<td>152</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35.3</td>
<td>0</td>
<td>639</td>
<td>94</td>
<td>132</td>
<td>85</td>
<td>72</td>
<td>0</td>
<td>5.62</td>
<td>.</td>
<td>121</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35.3</td>
<td>1</td>
<td>672</td>
<td>89</td>
<td>114</td>
<td>75</td>
<td>60</td>
<td>45</td>
<td>.</td>
<td>.</td>
<td>174</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35.3</td>
<td>2</td>
<td>723</td>
<td>83</td>
<td>130</td>
<td>86</td>
<td>59</td>
<td>50</td>
<td>0.02</td>
<td>-0.11</td>
<td>183</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>914</td>
<td>66</td>
<td>95</td>
<td>56</td>
<td>32</td>
<td>-2</td>
<td>1.80</td>
<td>1.93</td>
<td>50</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>1035</td>
<td>58</td>
<td>91</td>
<td>54</td>
<td>25</td>
<td>8</td>
<td>1.64</td>
<td>.</td>
<td>54</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>831</td>
<td>72</td>
<td>114</td>
<td>65</td>
<td>20</td>
<td>11</td>
<td>-1.91</td>
<td>-1.90</td>
<td>52</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.4</td>
<td>0</td>
<td>796</td>
<td>75</td>
<td>118</td>
<td>68</td>
<td>58</td>
<td>-1</td>
<td>2.04</td>
<td>2.22</td>
<td>94</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.4</td>
<td>1</td>
<td>797</td>
<td>75</td>
<td>109</td>
<td>66</td>
<td>40</td>
<td>19</td>
<td>1.71</td>
<td>.</td>
<td>98</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.4</td>
<td>2</td>
<td>779</td>
<td>77</td>
<td>119</td>
<td>70</td>
<td>29</td>
<td>25</td>
<td>-2.54</td>
<td>-2.84</td>
<td>90</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.2</td>
<td>0</td>
<td>741</td>
<td>81</td>
<td>115</td>
<td>70</td>
<td>77</td>
<td>0</td>
<td>2.77</td>
<td>3.71</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.2</td>
<td>1</td>
<td>620</td>
<td>97</td>
<td>117</td>
<td>73</td>
<td>51</td>
<td>34</td>
<td>.</td>
<td>.</td>
<td>142</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.2</td>
<td>2</td>
<td>784</td>
<td>77</td>
<td>121</td>
<td>75</td>
<td>40</td>
<td>38</td>
<td>-1.55</td>
<td>-2.43</td>
<td>130</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.9</td>
<td>0</td>
<td>653</td>
<td>92</td>
<td>126</td>
<td>77</td>
<td>87</td>
<td>0</td>
<td>3.31</td>
<td>3.90</td>
<td>145</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.9</td>
<td>1</td>
<td>680</td>
<td>88</td>
<td>121</td>
<td>72</td>
<td>63</td>
<td>40</td>
<td>.</td>
<td>.</td>
<td>172</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.9</td>
<td>2</td>
<td>849</td>
<td>71</td>
<td>125</td>
<td>78</td>
<td>49</td>
<td>48</td>
<td>-2.33</td>
<td>-2.22</td>
<td>163</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>834</td>
<td>72</td>
<td>101</td>
<td>56</td>
<td>44</td>
<td>-3</td>
<td>0.47</td>
<td>1.13</td>
<td>70</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>858</td>
<td>70</td>
<td>94</td>
<td>51</td>
<td>26</td>
<td>11</td>
<td>2.04</td>
<td>.</td>
<td>62</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>789</td>
<td>76</td>
<td>105</td>
<td>55</td>
<td>24</td>
<td>21</td>
<td>-3.47</td>
<td>-3.32</td>
<td>76</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>18</td>
<td>0</td>
<td>769</td>
<td>78</td>
<td>111</td>
<td>62</td>
<td>63</td>
<td>-2</td>
<td>1.13</td>
<td>1.68</td>
<td>103</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>18</td>
<td>1</td>
<td>772</td>
<td>78</td>
<td>110</td>
<td>57</td>
<td>40</td>
<td>25</td>
<td>2.51</td>
<td>.</td>
<td>109</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>18</td>
<td>2</td>
<td>812</td>
<td>74</td>
<td>106</td>
<td>63</td>
<td>34</td>
<td>32</td>
<td>-3.62</td>
<td>-3.60</td>
<td>109</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.3</td>
<td>0</td>
<td>709</td>
<td>85</td>
<td>114</td>
<td>64</td>
<td>76</td>
<td>-1</td>
<td>2.76</td>
<td>3.25</td>
<td>125</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.3</td>
<td>1</td>
<td>728</td>
<td>82</td>
<td>101</td>
<td>59</td>
<td>54</td>
<td>37</td>
<td>-2.00</td>
<td>.</td>
<td>153</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.3</td>
<td>2</td>
<td>.</td>
<td>.</td>
<td>126</td>
<td>69</td>
<td>44</td>
<td>33</td>
<td>-2.46</td>
<td>-2.93</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>730</td>
<td>82</td>
<td>119</td>
<td>82</td>
<td>68</td>
<td>-2</td>
<td>.</td>
<td>.</td>
<td>110</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>812</td>
<td>74</td>
<td>115</td>
<td>72</td>
<td>42</td>
<td>27</td>
<td>.</td>
<td>.</td>
<td>115</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>796</td>
<td>75</td>
<td>129</td>
<td>80</td>
<td>40</td>
<td>27</td>
<td>.</td>
<td>-3.61</td>
<td>113</td>
</tr>
</tbody>
</table>
Subject 17
Male
Height = 184 cm
Weight = 60 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>672</td>
<td>89</td>
<td>94</td>
<td>61</td>
<td>11</td>
<td>-4</td>
<td>1.26</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>665</td>
<td>90</td>
<td>105</td>
<td>68</td>
<td>11</td>
<td>-2</td>
<td>0.34</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>657</td>
<td>91</td>
<td>108</td>
<td>67</td>
<td>15</td>
<td>1</td>
<td>1.34</td>
<td>1.46</td>
<td>27</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.4</td>
<td>0</td>
<td>563</td>
<td>107</td>
<td>141</td>
<td>88</td>
<td>70</td>
<td>-1</td>
<td>2.88</td>
<td>3.82</td>
<td>115</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.4</td>
<td>1</td>
<td>587</td>
<td>102</td>
<td>121</td>
<td>76</td>
<td>41</td>
<td>25</td>
<td>3.31</td>
<td></td>
<td>109</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.4</td>
<td>2</td>
<td>560</td>
<td>107</td>
<td>137</td>
<td>83</td>
<td>47</td>
<td>27</td>
<td>4.03</td>
<td>3.66</td>
<td>124</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.6</td>
<td>0</td>
<td>507</td>
<td>118</td>
<td>159</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
<td>5.10</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.6</td>
<td>1</td>
<td>494</td>
<td>121</td>
<td>166</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.6</td>
<td>2</td>
<td>505</td>
<td>119</td>
<td>128</td>
<td>74</td>
<td>55</td>
<td>42</td>
<td>4.41</td>
<td>4.68</td>
<td>162</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.6</td>
<td>0</td>
<td>467</td>
<td>128</td>
<td>124</td>
<td>70</td>
<td>93</td>
<td>0</td>
<td>7.01</td>
<td>7.38</td>
<td>155</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.6</td>
<td>1</td>
<td>363</td>
<td>165</td>
<td>109</td>
<td>71</td>
<td>59</td>
<td>55</td>
<td>5.26</td>
<td></td>
<td>190</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.6</td>
<td>2</td>
<td>881</td>
<td>68</td>
<td>99</td>
<td>56</td>
<td>71</td>
<td>45</td>
<td>6.15</td>
<td>5.75</td>
<td>193</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>653</td>
<td>92</td>
<td>93</td>
<td>60</td>
<td>33</td>
<td>-3</td>
<td>3.17</td>
<td>2.84</td>
<td>50</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>729</td>
<td>82</td>
<td>84</td>
<td>49</td>
<td>22</td>
<td>3</td>
<td>2.64</td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>693</td>
<td>87</td>
<td>93</td>
<td>55</td>
<td>22</td>
<td>7</td>
<td>2.92</td>
<td>3.01</td>
<td>48</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>0</td>
<td>621</td>
<td>97</td>
<td>104</td>
<td>62</td>
<td>66</td>
<td>-2</td>
<td>3.54</td>
<td>3.76</td>
<td>105</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>1</td>
<td>617</td>
<td>97</td>
<td>102</td>
<td>58</td>
<td>40</td>
<td>19</td>
<td></td>
<td></td>
<td>97</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>2</td>
<td>610</td>
<td>98</td>
<td>115</td>
<td>64</td>
<td>41</td>
<td>18</td>
<td>3.60</td>
<td>3.72</td>
<td>98</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.8</td>
<td>0</td>
<td>526</td>
<td>114</td>
<td>108</td>
<td>62</td>
<td>73</td>
<td>-1</td>
<td>4.34</td>
<td>4.44</td>
<td>120</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.8</td>
<td>1</td>
<td>494</td>
<td>121</td>
<td>99</td>
<td>60</td>
<td>53</td>
<td>35</td>
<td>3.06</td>
<td></td>
<td>147</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.8</td>
<td>2</td>
<td>539</td>
<td>111</td>
<td>109</td>
<td>67</td>
<td>55</td>
<td>31</td>
<td>3.46</td>
<td>3.76</td>
<td>143</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.4</td>
<td>0</td>
<td>462</td>
<td>130</td>
<td>118</td>
<td>64</td>
<td>76</td>
<td>0</td>
<td>5.38</td>
<td>6.46</td>
<td>126</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.4</td>
<td>1</td>
<td>427</td>
<td>141</td>
<td>104</td>
<td>61</td>
<td>58</td>
<td>42</td>
<td>4.43</td>
<td></td>
<td>167</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.4</td>
<td>2</td>
<td>447</td>
<td>134</td>
<td>103</td>
<td>64</td>
<td>64</td>
<td>34</td>
<td>5.64</td>
<td>4.93</td>
<td>162</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>635</td>
<td>94</td>
<td>89</td>
<td>54</td>
<td>54</td>
<td>-3</td>
<td>2.96</td>
<td></td>
<td>2.92</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>637</td>
<td>94</td>
<td>86</td>
<td>49</td>
<td>32</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>609</td>
<td>99</td>
<td>98</td>
<td>56</td>
<td>33</td>
<td>13</td>
<td>3.44</td>
<td>3.17</td>
<td>77</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>0</td>
<td>563</td>
<td>106</td>
<td>116</td>
<td>65</td>
<td>69</td>
<td>-2</td>
<td>3.67</td>
<td>4.11</td>
<td>111</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>1</td>
<td>554</td>
<td>108</td>
<td>107</td>
<td>63</td>
<td>48</td>
<td>26</td>
<td>2.63</td>
<td></td>
<td>124</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>2</td>
<td>535</td>
<td>112</td>
<td>105</td>
<td>67</td>
<td>42</td>
<td>27</td>
<td>3.52</td>
<td>3.45</td>
<td>115</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>0</td>
<td>476</td>
<td>126</td>
<td>115</td>
<td>71</td>
<td>84</td>
<td>-2</td>
<td>5.16</td>
<td>6.00</td>
<td>137</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>1</td>
<td>478</td>
<td>126</td>
<td>117</td>
<td>72</td>
<td>58</td>
<td>39</td>
<td></td>
<td></td>
<td>161</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>2</td>
<td>490</td>
<td>122</td>
<td>107</td>
<td>69</td>
<td>57</td>
<td>36</td>
<td>4.05</td>
<td>4.03</td>
<td>153</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>540</td>
<td>111</td>
<td>116</td>
<td>78</td>
<td>66</td>
<td>-3</td>
<td>5.14</td>
<td>5.06</td>
<td>106</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>519</td>
<td>116</td>
<td>111</td>
<td>77</td>
<td>49</td>
<td>24</td>
<td>2.82</td>
<td></td>
<td>121</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>547</td>
<td>110</td>
<td>118</td>
<td>77</td>
<td>46</td>
<td>25</td>
<td>3.44</td>
<td>3.33</td>
<td>118</td>
</tr>
</tbody>
</table>
**APPENDIX D: INDIVIDUAL SUBJECT DATA, EXPERIMENT 1**

**Subject 18**

**Male**

**Height = 178 cm**

**Weight = 73 kg**

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1107</td>
<td>54</td>
<td>105</td>
<td>62</td>
<td>16</td>
<td>-3</td>
<td>1.25</td>
<td>73</td>
<td>20</td>
<td>126</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1061</td>
<td>57</td>
<td>114</td>
<td>62</td>
<td>14</td>
<td>0</td>
<td>0.36</td>
<td>.</td>
<td>20</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>862</td>
<td>70</td>
<td>120</td>
<td>65</td>
<td>16</td>
<td>3</td>
<td>-0.15</td>
<td>-0.19</td>
<td>26</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>0</td>
<td>888</td>
<td>68</td>
<td>124</td>
<td>79</td>
<td>43</td>
<td>-1</td>
<td>4.77</td>
<td>5.57</td>
<td>58</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>1</td>
<td>999</td>
<td>60</td>
<td>127</td>
<td>75</td>
<td>44</td>
<td>36</td>
<td>1.54</td>
<td>.</td>
<td>109</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.6</td>
<td>2</td>
<td>753</td>
<td>80</td>
<td>136</td>
<td>76</td>
<td>54</td>
<td>31</td>
<td>2.16</td>
<td>1.84</td>
<td>117</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.8</td>
<td>0</td>
<td>889</td>
<td>67</td>
<td>126</td>
<td>79</td>
<td>70</td>
<td>-1</td>
<td>6.56</td>
<td>6.74</td>
<td>94</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.8</td>
<td>1</td>
<td>852</td>
<td>70</td>
<td>123</td>
<td>77</td>
<td>63</td>
<td>57</td>
<td>.</td>
<td></td>
<td>165</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>0</td>
<td>796</td>
<td>75</td>
<td>136</td>
<td>84</td>
<td>75</td>
<td>0</td>
<td>8.41</td>
<td>.</td>
<td>104</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>1</td>
<td>793</td>
<td>76</td>
<td>135</td>
<td>79</td>
<td>59</td>
<td>63</td>
<td>5.31</td>
<td>.</td>
<td>169</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.9</td>
<td>2</td>
<td>733</td>
<td>82</td>
<td>153</td>
<td>83</td>
<td>72</td>
<td>50</td>
<td>5.62</td>
<td>5.44</td>
<td>168</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>1014</td>
<td>59</td>
<td>109</td>
<td>59</td>
<td>29</td>
<td>-3</td>
<td>3.47</td>
<td>3.56</td>
<td>35</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>1052</td>
<td>57</td>
<td>101</td>
<td>57</td>
<td>26</td>
<td>11</td>
<td>3.11</td>
<td>.</td>
<td>50</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>825</td>
<td>73</td>
<td>115</td>
<td>61</td>
<td>28</td>
<td>10</td>
<td>0.75</td>
<td>0.74</td>
<td>53</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>0</td>
<td>970</td>
<td>62</td>
<td>117</td>
<td>62</td>
<td>53</td>
<td>-2</td>
<td>3.86</td>
<td>4.12</td>
<td>70</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>1</td>
<td>959</td>
<td>63</td>
<td>126</td>
<td>67</td>
<td>42</td>
<td>29</td>
<td>0.38</td>
<td>.</td>
<td>98</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.2</td>
<td>2</td>
<td>804</td>
<td>75</td>
<td>132</td>
<td>68</td>
<td>41</td>
<td>26</td>
<td>0.91</td>
<td>1.02</td>
<td>92</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>0</td>
<td>905</td>
<td>66</td>
<td>133</td>
<td>73</td>
<td>65</td>
<td>-2</td>
<td>5.04</td>
<td>5.46</td>
<td>86</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>926</td>
<td>65</td>
<td>133</td>
<td>73</td>
<td>75</td>
<td>60</td>
<td>1.30</td>
<td>.</td>
<td>144</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25</td>
<td>1</td>
<td>832</td>
<td>72</td>
<td>134</td>
<td>82</td>
<td>53</td>
<td>36</td>
<td>2.12</td>
<td>2.07</td>
<td>123</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>0</td>
<td>830</td>
<td>72</td>
<td>142</td>
<td>82</td>
<td>63</td>
<td>-1</td>
<td>5.39</td>
<td>.</td>
<td>85</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>1</td>
<td>813</td>
<td>74</td>
<td>134</td>
<td>78</td>
<td>57</td>
<td>64</td>
<td>2.51</td>
<td>.</td>
<td>165</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.6</td>
<td>2</td>
<td>1149</td>
<td>52</td>
<td>107</td>
<td>77</td>
<td>58</td>
<td>47</td>
<td>3.01</td>
<td>3.13</td>
<td>144</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>968</td>
<td>62</td>
<td>118</td>
<td>60</td>
<td>51</td>
<td>-3</td>
<td>3.42</td>
<td>3.69</td>
<td>67</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>1023</td>
<td>59</td>
<td>126</td>
<td>62</td>
<td>36</td>
<td>26</td>
<td>.</td>
<td></td>
<td>85</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>696</td>
<td>86</td>
<td>130</td>
<td>68</td>
<td>43</td>
<td>19</td>
<td>0.19</td>
<td>0.00</td>
<td>86</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>0</td>
<td>805</td>
<td>74</td>
<td>119</td>
<td>72</td>
<td>73</td>
<td>-2</td>
<td>3.88</td>
<td>.</td>
<td>97</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>1</td>
<td>925</td>
<td>65</td>
<td>120</td>
<td>66</td>
<td>51</td>
<td>43</td>
<td>0.19</td>
<td>.</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>2</td>
<td>880</td>
<td>68</td>
<td>109</td>
<td>70</td>
<td>46</td>
<td>30</td>
<td>0.86</td>
<td>0.80</td>
<td>104</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>0</td>
<td>904</td>
<td>66</td>
<td>127</td>
<td>70</td>
<td>65</td>
<td>-2</td>
<td>5.46</td>
<td>6.03</td>
<td>87</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>1</td>
<td>943</td>
<td>64</td>
<td>127</td>
<td>71</td>
<td>55</td>
<td>52</td>
<td>.</td>
<td></td>
<td>147</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>2</td>
<td>823</td>
<td>73</td>
<td>121</td>
<td>73</td>
<td>53</td>
<td>38</td>
<td>1.60</td>
<td>1.72</td>
<td>125</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>929</td>
<td>65</td>
<td>134</td>
<td>72</td>
<td>63</td>
<td>-2</td>
<td>3.00</td>
<td>3.10</td>
<td>84</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>843</td>
<td>71</td>
<td>121</td>
<td>67</td>
<td>38</td>
<td>46</td>
<td>.</td>
<td></td>
<td>115</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>899</td>
<td>67</td>
<td>137</td>
<td>71</td>
<td>40</td>
<td>34</td>
<td>0.40</td>
<td>0.21</td>
<td>102</td>
</tr>
</tbody>
</table>
Subject 19

Male

Height = 182 cm

Weight = 79 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1052</td>
<td>57</td>
<td>125</td>
<td>71</td>
<td>14</td>
<td>1</td>
<td>0.25</td>
<td>0.17</td>
<td>19</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1102</td>
<td>54</td>
<td>133</td>
<td>79</td>
<td>14</td>
<td>-4</td>
<td>1.23</td>
<td>.</td>
<td>12</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1059</td>
<td>57</td>
<td>129</td>
<td>73</td>
<td>9</td>
<td>-4</td>
<td>-0.58</td>
<td>-0.36</td>
<td>6</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.5</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.5</td>
<td>1</td>
<td>760</td>
<td>79</td>
<td>133</td>
<td>91</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.5</td>
<td>2</td>
<td>878</td>
<td>68</td>
<td>169</td>
<td>103</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.7</td>
<td>0</td>
<td>793</td>
<td>76</td>
<td>151</td>
<td>97</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.7</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.7</td>
<td>2</td>
<td>676</td>
<td>89</td>
<td>188</td>
<td>116</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.7</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.7</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.7</td>
<td>2</td>
<td>768</td>
<td>78</td>
<td>170</td>
<td>116</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>1153</td>
<td>52</td>
<td>130</td>
<td>73</td>
<td>39</td>
<td>-3</td>
<td>2.35</td>
<td>2.35</td>
<td>45</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>1118</td>
<td>54</td>
<td>120</td>
<td>67</td>
<td>28</td>
<td>14</td>
<td>2.22</td>
<td>.</td>
<td>52</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>1010</td>
<td>59</td>
<td>137</td>
<td>73</td>
<td>.</td>
<td>-10</td>
<td>0.89</td>
<td>1.51</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>0</td>
<td>944</td>
<td>64</td>
<td>138</td>
<td>81</td>
<td>61</td>
<td>-2</td>
<td>3.05</td>
<td>3.30</td>
<td>74</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>1</td>
<td>981</td>
<td>61</td>
<td>125</td>
<td>76</td>
<td>47</td>
<td>29</td>
<td>.</td>
<td>.</td>
<td>96</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.1</td>
<td>2</td>
<td>921</td>
<td>65</td>
<td>143</td>
<td>78</td>
<td>43</td>
<td>26</td>
<td>.</td>
<td>2.20</td>
<td>88</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.9</td>
<td>0</td>
<td>801</td>
<td>75</td>
<td>152</td>
<td>87</td>
<td>88</td>
<td>-2</td>
<td>.</td>
<td>4.24</td>
<td>109</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.9</td>
<td>1</td>
<td>798</td>
<td>75</td>
<td>123</td>
<td>72</td>
<td>65</td>
<td>48</td>
<td>.</td>
<td>.</td>
<td>143</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>24.9</td>
<td>2</td>
<td>783</td>
<td>77</td>
<td>148</td>
<td>93</td>
<td>50</td>
<td>39</td>
<td>.</td>
<td>3.50</td>
<td>112</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.5</td>
<td>0</td>
<td>703</td>
<td>85</td>
<td>164</td>
<td>89</td>
<td>82</td>
<td>-1</td>
<td>.</td>
<td>6.09</td>
<td>103</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.5</td>
<td>1</td>
<td>703</td>
<td>85</td>
<td>130</td>
<td>74</td>
<td>60</td>
<td>60</td>
<td>.</td>
<td>.</td>
<td>153</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.5</td>
<td>2</td>
<td>684</td>
<td>88</td>
<td>164</td>
<td>104</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>5.70</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>987</td>
<td>61</td>
<td>116</td>
<td>66</td>
<td>48</td>
<td>-3</td>
<td>1.53</td>
<td>1.59</td>
<td>57</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>1000</td>
<td>60</td>
<td>102</td>
<td>57</td>
<td>36</td>
<td>22</td>
<td>1.56</td>
<td>.</td>
<td>74</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>990</td>
<td>61</td>
<td>119</td>
<td>69</td>
<td>33</td>
<td>19</td>
<td>0.66</td>
<td>1.05</td>
<td>65</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>0</td>
<td>837</td>
<td>72</td>
<td>139</td>
<td>85</td>
<td>68</td>
<td>-3</td>
<td>.</td>
<td>.</td>
<td>83</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>1</td>
<td>898</td>
<td>67</td>
<td>131</td>
<td>75</td>
<td>52</td>
<td>36</td>
<td>.</td>
<td>.</td>
<td>111</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>2</td>
<td>832</td>
<td>72</td>
<td>143</td>
<td>85</td>
<td>44</td>
<td>37</td>
<td>.</td>
<td>-0.12</td>
<td>103</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>0</td>
<td>807</td>
<td>74</td>
<td>162</td>
<td>97</td>
<td>73</td>
<td>-2</td>
<td>.</td>
<td>.</td>
<td>89</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>1</td>
<td>790</td>
<td>76</td>
<td>139</td>
<td>82</td>
<td>56</td>
<td>51</td>
<td>.</td>
<td>.</td>
<td>136</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.1</td>
<td>2</td>
<td>933</td>
<td>64</td>
<td>153</td>
<td>92</td>
<td>51</td>
<td>45</td>
<td>.</td>
<td>0.51</td>
<td>122</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>929</td>
<td>65</td>
<td>129</td>
<td>77</td>
<td>84</td>
<td>-2</td>
<td>0.07</td>
<td>1.05</td>
<td>103</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>965</td>
<td>62</td>
<td>95</td>
<td>58</td>
<td>54</td>
<td>37</td>
<td>-0.35</td>
<td>.</td>
<td>116</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>945</td>
<td>64</td>
<td>129</td>
<td>69</td>
<td>54</td>
<td>34</td>
<td>-0.55</td>
<td>-0.38</td>
<td>112</td>
</tr>
</tbody>
</table>
Subject 20

Male

Height = 185 cm

Weight = 77 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1011</td>
<td>59</td>
<td>127</td>
<td>75</td>
<td>-4</td>
<td>1</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>959</td>
<td>63</td>
<td>129</td>
<td>76</td>
<td>15</td>
<td>1</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.4</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-2</td>
<td>4.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td>3.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.6</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1</td>
<td>5.93</td>
<td>6.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>31.6</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>49</td>
<td>6.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.6</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>7.29</td>
<td>7.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.6</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>66</td>
<td>4.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>34.6</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>64</td>
<td>3.61</td>
<td>3.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>887</td>
<td>68</td>
<td>110</td>
<td>66</td>
<td>-7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>968</td>
<td>62</td>
<td>104</td>
<td>64</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>2</td>
<td>922</td>
<td>65</td>
<td>117</td>
<td>70</td>
<td>15</td>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>26.4</td>
<td>0</td>
<td>813</td>
<td>74</td>
<td>120</td>
<td>70</td>
<td>-3</td>
<td>4.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>26.4</td>
<td>1</td>
<td>746</td>
<td>80</td>
<td>116</td>
<td>68</td>
<td>28</td>
<td>3.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>26.4</td>
<td>2</td>
<td>792</td>
<td>76</td>
<td>130</td>
<td>74</td>
<td>30</td>
<td>0.96</td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>31.6</td>
<td>0</td>
<td>665</td>
<td>90</td>
<td>120</td>
<td>66</td>
<td>-2</td>
<td>5.17</td>
<td>4.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>31.6</td>
<td>1</td>
<td>636</td>
<td>94</td>
<td>107</td>
<td>55</td>
<td>43</td>
<td>3.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>31.6</td>
<td>2</td>
<td>729</td>
<td>82</td>
<td>131</td>
<td>73</td>
<td>47</td>
<td>1.36</td>
<td>1.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>34.6</td>
<td>0</td>
<td>521</td>
<td>115</td>
<td>121</td>
<td>67</td>
<td>-1</td>
<td>6.16</td>
<td>6.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>34.6</td>
<td>1</td>
<td>630</td>
<td>95</td>
<td>112</td>
<td>65</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>34.6</td>
<td>2</td>
<td>566</td>
<td>106</td>
<td>133</td>
<td>82</td>
<td>59</td>
<td>2.67</td>
<td>2.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>842</td>
<td>71</td>
<td>123</td>
<td>63</td>
<td></td>
<td></td>
<td>2.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>1</td>
<td>1</td>
<td>836</td>
<td>72</td>
<td>114</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>2</td>
<td>866</td>
<td>69</td>
<td>130</td>
<td>72</td>
<td></td>
<td></td>
<td>-0.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>0</td>
<td>755</td>
<td>79</td>
<td>129</td>
<td>66</td>
<td></td>
<td>3.99</td>
<td>4.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>1</td>
<td>779</td>
<td>77</td>
<td>131</td>
<td>62</td>
<td></td>
<td>2.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.8</td>
<td>2</td>
<td>715</td>
<td>84</td>
<td>132</td>
<td>72</td>
<td></td>
<td>0.58</td>
<td>0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>0</td>
<td>656</td>
<td>91</td>
<td>127</td>
<td>71</td>
<td></td>
<td>5.94</td>
<td>5.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>1</td>
<td>642</td>
<td>93</td>
<td>131</td>
<td>66</td>
<td></td>
<td>3.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23</td>
<td>2</td>
<td>660</td>
<td>91</td>
<td>129</td>
<td>75</td>
<td></td>
<td>1.72</td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>705</td>
<td>85</td>
<td>136</td>
<td>77</td>
<td>-3</td>
<td></td>
<td></td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>779</td>
<td>77</td>
<td>128</td>
<td>73</td>
<td>47</td>
<td>36</td>
<td></td>
<td></td>
<td>109</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>808</td>
<td>74</td>
<td>139</td>
<td>79</td>
<td>56</td>
<td>38</td>
<td>-1.33</td>
<td>123</td>
<td></td>
</tr>
</tbody>
</table>
Subject 21
Male
Height = 174 cm
Weight = 68 kg

<table>
<thead>
<tr>
<th>GLEV</th>
<th>TILT</th>
<th>RPM</th>
<th>ACT</th>
<th>B2B</th>
<th>HRT</th>
<th>SBP</th>
<th>DBP</th>
<th>LF</th>
<th>RF</th>
<th>RC40</th>
<th>RC100</th>
<th>PCTWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>736</td>
<td>82</td>
<td>134</td>
<td>65</td>
<td>-3</td>
<td>1.78</td>
<td>0.53</td>
<td>1.78</td>
<td>0.53</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>832</td>
<td>72</td>
<td>108</td>
<td>58</td>
<td>-2</td>
<td>0.46</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>774</td>
<td>76</td>
<td>127</td>
<td>67</td>
<td>0</td>
<td>4.60</td>
<td>4.60</td>
<td>4.60</td>
<td>4.60</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>0</td>
<td>670</td>
<td>90</td>
<td>131</td>
<td>85</td>
<td>-1</td>
<td>3.98</td>
<td>4.60</td>
<td>4.60</td>
<td>4.60</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>1</td>
<td>677</td>
<td>89</td>
<td>131</td>
<td>85</td>
<td>29</td>
<td>3.48</td>
<td>3.48</td>
<td>3.48</td>
<td>3.48</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>26.7</td>
<td>2</td>
<td>672</td>
<td>89</td>
<td>145</td>
<td>88</td>
<td>28</td>
<td>1.88</td>
<td>1.88</td>
<td>1.88</td>
<td>1.88</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>0</td>
<td>595</td>
<td>101</td>
<td>149</td>
<td>100</td>
<td>0</td>
<td>4.95</td>
<td>5.27</td>
<td>5.27</td>
<td>5.27</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>1</td>
<td>564</td>
<td>106</td>
<td>136</td>
<td>90</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>32</td>
<td>2</td>
<td>610</td>
<td>98</td>
<td>153</td>
<td>95</td>
<td>44</td>
<td>2.21</td>
<td>2.21</td>
<td>2.21</td>
<td>2.21</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35</td>
<td>0</td>
<td>586</td>
<td>102</td>
<td>121</td>
<td>100</td>
<td>0</td>
<td>6.21</td>
<td>6.59</td>
<td>6.59</td>
<td>6.59</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>35</td>
<td>2</td>
<td>863</td>
<td>69</td>
<td>127</td>
<td>88</td>
<td>57</td>
<td>3.45</td>
<td>3.20</td>
<td>3.20</td>
<td>3.20</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>805</td>
<td>75</td>
<td>110</td>
<td>59</td>
<td>-3</td>
<td>3.39</td>
<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>1</td>
<td>824</td>
<td>73</td>
<td>110</td>
<td>58</td>
<td>8</td>
<td>1.97</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.36</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>793</td>
<td>76</td>
<td>123</td>
<td>61</td>
<td>8</td>
<td>0.95</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>0</td>
<td>726</td>
<td>83</td>
<td>125</td>
<td>72</td>
<td>-2</td>
<td>3.99</td>
<td>4.13</td>
<td>4.13</td>
<td>4.13</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>1</td>
<td>713</td>
<td>84</td>
<td>124</td>
<td>69</td>
<td>25</td>
<td>2.77</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>21</td>
<td>18.3</td>
<td>2</td>
<td>702</td>
<td>85</td>
<td>143</td>
<td>76</td>
<td>23</td>
<td>0.81</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>0</td>
<td>613</td>
<td>98</td>
<td>146</td>
<td>86</td>
<td>-1</td>
<td>4.50</td>
<td>4.82</td>
<td>4.82</td>
<td>4.82</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>1</td>
<td>611</td>
<td>98</td>
<td>126</td>
<td>74</td>
<td>41</td>
<td>1.99</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>25.1</td>
<td>2</td>
<td>859</td>
<td>70</td>
<td>119</td>
<td>79</td>
<td>37</td>
<td>1.81</td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>0</td>
<td>526</td>
<td>114</td>
<td>145</td>
<td>90</td>
<td>-1</td>
<td>5.31</td>
<td>5.69</td>
<td>5.69</td>
<td>5.69</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>1</td>
<td>550</td>
<td>109</td>
<td>124</td>
<td>77</td>
<td>51</td>
<td>3.92</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>21</td>
<td>28.7</td>
<td>2</td>
<td>824</td>
<td>73</td>
<td>129</td>
<td>78</td>
<td>49</td>
<td>2.37</td>
<td>2.24</td>
<td>2.24</td>
<td>2.24</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>744</td>
<td>81</td>
<td>140</td>
<td>78</td>
<td>-3</td>
<td>3.30</td>
<td>3.41</td>
<td>3.41</td>
<td>3.41</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>729</td>
<td>82</td>
<td>134</td>
<td>68</td>
<td>17</td>
<td>1.83</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
<td>0</td>
<td>2</td>
<td>666</td>
<td>90</td>
<td>146</td>
<td>73</td>
<td>18</td>
<td>0.70</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>0</td>
<td>685</td>
<td>88</td>
<td>150</td>
<td>84</td>
<td>-2</td>
<td>4.00</td>
<td>4.18</td>
<td>4.18</td>
<td>4.18</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>1</td>
<td>650</td>
<td>92</td>
<td>144</td>
<td>78</td>
<td>29</td>
<td>2.88</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>17.9</td>
<td>2</td>
<td>645</td>
<td>93</td>
<td>150</td>
<td>89</td>
<td>29</td>
<td>1.12</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>0</td>
<td>601</td>
<td>100</td>
<td>157</td>
<td>93</td>
<td>-1</td>
<td>4.62</td>
<td>4.93</td>
<td>4.93</td>
<td>4.93</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>1</td>
<td>598</td>
<td>100</td>
<td>147</td>
<td>81</td>
<td>38</td>
<td>3.98</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1.2</td>
<td>45</td>
<td>23.2</td>
<td>2</td>
<td>611</td>
<td>98</td>
<td>142</td>
<td>90</td>
<td>41</td>
<td>1.89</td>
<td>1.63</td>
<td>1.63</td>
<td>1.63</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>654</td>
<td>92</td>
<td>134</td>
<td>83</td>
<td>-2</td>
<td>0.58</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>1</td>
<td>606</td>
<td>99</td>
<td>139</td>
<td>78</td>
<td>33</td>
<td>-2.27</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>2</td>
<td>671</td>
<td>89</td>
<td>143</td>
<td>81</td>
<td>29</td>
<td>-2.66</td>
<td>-2.81</td>
<td>-2.81</td>
<td>-2.81</td>
</tr>
</tbody>
</table>
Appendix E

Advertising and health forms, Experiment 2
E.1 Poster Advertisement

Do you want to get in shape, while furthering the field of human space research?

WANTED:

Couch Potatoes

Seeking male subjects for an eight-week exercise study. Participants will be compensated up to $400 for their time and receive free fitness screenings. Applicants must be healthy, but not currently involved in a regular exercise program. Contact space-exercise@gmt.edu
E.2 Biomechanical Questionnaire (pre-participation)

Bone, Muscle, and Joint History

Please briefly explain any questions in which you answered, “Yes.”

Yes ☐ No ☐ ☐ Do you have a history of ankle, knee, or hip injuries?

Yes ☐ No ☐ ☐ Do you currently have any knee, ankle, or hip pain/discomfort?

Yes ☐ No ☐ ☐ Have you ever had ACL, PCL, MCL, or LCL surgery?

Yes ☐ No ☐ ☐ Do you have arthritis in your ankle, knee, or hip?

Yes ☐ No ☐ ☐ Have you ever strained a muscle in your leg (hip, quad, calf, etc.)? If Yes, which muscle and how long ago?

Yes ☐ No ☐ ☐ Do you have a history of back or neck injuries?

Yes ☐ No ☐ ☐ Do you currently have any back or neck pain/discomfort?

Yes ☐ No ☐ ☐ Have you ever “herniated a disk” in your back from heavy lifting?

Yes ☐ No ☐ ☐ Have you ever broken a bone in your leg (including ankle and foot)? If Yes, which bone(s) and how long ago?
Exercise History

Please briefly explain any questions in which you answered, “Yes.”

Yes [ ] No [ ] Do you exercise regularly?
If Yes, what form? Cardiovascular or strength training? (circle)
How many days per week? __________
How many hours per exercise session? __________

If strength training, please briefly describe your leg exercise protocol. (e.g., # days per week, which exercises, reps x sets, etc.)

If cardiovascular training, please briefly describe your exercise protocol. (e.g., activity, # days per week, etc.)

Yes [ ] No [ ] Do you have any joint or muscle pain when exercising?

Yes [ ] No [ ] Have you ever sustained an injury while exercising?
If Yes, which muscle/joint and how long ago?

Yes [ ] No [ ] Do you have any joint or muscle pain after strenuous exercise?
E.3 Health Questionnaire (pre-participation)

AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire

History
You have had:
___ a heart attack
___ heart surgery
___ cardiac catheterization
___ coronary angioplasty (PTCA)
___ pacemaker/implantable cardiac defibrillator/rhythm disturbance
___ heart valve disease
___ heart failure
___ heart transplantation
___ congenital heart disease

Symptoms
___ You experience chest discomfort with exertion.
___ You experience unreasonable breathlessness.
___ You experience dizziness, fainting, or blackouts.
___ You take heart medications.

Other health issues
___ You have diabetes.
___ You have asthma or other lung disease.
___ You have burning or cramping sensation in your lower legs when walking short distances.
___ You have musculoskeletal problems that limit your physical activity
___ You have concerns about the safety of exercise.
___ You take prescription medication(s).
___ You are pregnant.

Cardiovascular risk factors
___ You are a man older than 45 years.
___ You are a woman older than 55 years, have had a hysterectomy, or are postmenopausal.
___ You smoke, or quit smoking within the previous 6 months.
___ Your blood pressure is > 140/90 mmHg
___ You do not know your blood pressure.
___ You take blood pressure medication.
___ Your blood cholesterol level is > 200 mg/dL.
___ You do not know your cholesterol level.
___ You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister).
___ You are physically inactive (i.e. you get < 30 minutes of physical activity on at least 3 days per week).
___ You are > 20 pounds overweight.
___ None of the above

If you marked any of these statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You may need to use a facility with medically qualified staff.

If you marked two or more of the statements in this section you should consult your physician or other appropriate health care provider before engaging in exercise. You might benefit from using a facility with professionally qualified exercise staff to guide your exercise program.

You should be able to exercise safely without consulting your physician or other appropriate health care provider in a self-guided program or almost any facility that meets your exercise program needs.
E.4 Exit Survey (post-participation)

Exit Survey
Artificial Gravity/Exercise Study

NAME_____________________

1. Did you feel that exercising in the dark felt unnatural?
   a. If so, how long did it take (if ever) for it to feel fairly natural?

2. What was the most uncomfortable part (if any) of exercising on the centrifuge?

3. What was the best part (if any) of exercising on the centrifuge?

4. Did you ever feel motion sick on the centrifuge?

5. Did you eventually forget that you were spinning?
   a. If so, how many sessions did it take for this to start happening?
   b. Once you started forgetting about spinning, how long into each session did it take for you to forget you were spinning?

6. In general, did your sessions feel too long, not long enough, or just about right to get you into shape?

7. In general, do you think your target heart rates gave you a good workout?

8. At the beginning of the exercise program, did you feel any sore muscles?
   a. If so, which muscles?

9. Do you think stair-stepping is a good type of exercise to do on the centrifuge?
   a. If not, what type of exercise would you have preferred, and why?

10. Did you think the stretching that you did was sufficient?
11. Did you have any trouble watching or hearing the movie while exercising on the centrifuge?

12. Did the change of direction every other day bother you?

13. What type of arm exercise did you normally do? (Please describe the upward motion and which muscles it worked the most.)
   
   a. Did you vary the type of arm exercise you did?

14. Did you notice the Coriolis accelerations – that is, lateral movements of your knees, hips, or arms?
   
   a. If so, on what part of your body did you most notice it?
   
   b. Did you stop feeling it after a while?
   
   c. If so, how long?

15. If NASA decided to implement centrifugation and exercise for astronauts, do you have any suggestions or recommendations for how they could improve this system?

16. Do you have anything else you’d like to share that you thought was unique to exercising in a rotating environment?
Appendix F

Thesis defense slides
Exercise protocols during short-radius centrifugation for artificial gravity

Jessica L. Edmonds
Doctoral Thesis Defense
April 28, 2008

Committee
Laurence Young, chair
Roger Mark
Thomas Jarchow
Lars Oddsson

Thesis outline

• Background
  – Motivation for current study
  – Contributions
• Experiment 1: ESA tilting centrifuge
• Experiment 2: MIT short-radius centrifuge
• Conclusion
  – Thesis summary
  – Recommendations
Spaceflight deconditioning

1. Bone mineral density loss on the order of 0.5-2.0% per month, depending on location
   - Lang et al. 2014

2. Decreased muscle strength (25% in a month for leg extensors), also muscle mass and volume
   - Garg et al. 1999; Leytes et al. 2000; Cigano et al. 2004; Thornton 1988

3. Cardiovascular deconditioning
   - 20% of astronauts experience orthostatic intolerance postflight
   - Voss et al. 2002

**Problem statement**

Long-duration spaceflight results in bone, muscle, and cardiovascular losses. Effective countermeasures must be developed before we attempt a long-duration interplanetary mission.

---

**Motivation**

**Exercise**
- Greenleaf et al. 1989; Conrettea and Sandell 1997; Levine et al. 1996; Tesch and Berg 1987; Barman and Caussai 2000; Moone et al. 2001; Shackelford et al. 2004

Countermeasures to spaceflight deconditioning
Motivation

Exercise
Greenleaf et al. 1999; Convertino and Sandler 1995; Levine et al. 1996; Tesch and Berg 1997; Demmen and Canuso 2000; Moore et al. 2001; Shackerford et al. 2004

Pharmaceuticals
Buckley 2006; Fernando et al. 2002; Brown and Eckberg 1997; Ramsdell et al. 2001; Piatt et al. 2006

Countermeasures to spaceflight deconditioning

Motivation

Exercise
Greenleaf et al. 1999; Convertino and Sandler 1995; Levine et al. 1996; Tesch and Berg 1997; Demmen and Canuso 2000; Moore et al. 2001; Shackerford et al. 2004

Pharmaceuticals
Buckley 2006; Fernando et al. 2002; Brown and Eckberg 1997; Ramsdell et al. 2001; Piatt et al. 2006

Countermeasures to spaceflight deconditioning

Russian countermeasure suits: Penguin, Chibis
Koslovskaya and Grigoriev 2004; Fortney 1991; Charles and Lathers 1994
Motivation

Iwase et al 2003:
Cycling on a centrifuge helps with g-tolerance

**Research Aim #1**
Quantify the physiological responses to g-gradients, and determine if stepping in place attenuates these responses

Cycling on a centrifuge helps to prevent bedrest deconditioning

**Research Aim #2**
Investigate the fitness benefits (for healthy subjects) of stair-stepping on a centrifuge

Contributions

1. Measurement of physiological responses to varying axial g-gradient (*Experiment 1*)

2. Measurement of effectiveness of stair-stepping on a centrifuge (*Experiment 2*)
   - Use of a stair-stepper
   - Long (eight week) protocol
   - Measures of fitness rather than prevention of deconditioning
   - Addition of MIT centrifuge hardware elements
Experiment 1: The effect of light exercise on the physiological response to a gravity gradient

The University of Antwerp, Belgium
European Space Agency Short Arm Human Centrifuge

Calculating $G_z$

Total magnitude of vector along body axis:

$$G_z = AG\cos\theta + g\sin\theta$$

$AG = r\omega^2$
Tilt angle determines g-gradient

\[ g\text{-gradient} = \frac{(G_{Z, \text{feet}} - G_{Z, \text{head}})}{G_{Z, \text{feet}}} \]

\[ G_{Z} = AG\cos\theta + gs\sin\theta \]

\( (AG=r\omega^2) \)

---

**Protocol**

- Gz at heart:
  - still: 0.7-g, 1.0-g, 1.2-g

- Angular positions:
  - Upright
  - 45 degrees
  - 21 degrees
  - 0 degrees

**Legend**

- One foot
- Two feet
- Staying in place
Motivation and hypothesis

1. Short- vs. large-radius centrifugation results in different axial g-gradients
2. High g-gradients may be more stressful
   Unusual physiological environment, high G_z at the feet
   (Burton and Meeker 1992; Hasselbrecher and Young 1997)
   The problem may be even worse for astronauts who have already become deconditioned
3. Rhythmic contractions of the legs may aid in venous return, reducing the effect of high G_z and g-gradients on physiological responses
   (Pelack and Wood 1949; Iwase et al 2003)

Hypothesis

Calf volume, heart rate, and blood pressure will increase with increasing G_z and increasing g-gradient, but light exercise will mitigate these effects

Measurements and statistics

Measurements
1. Calf volume
   Hohanson indium shin gauges
   Leg circumference for volume measurements
   Whitney 1993
2. Heart rate and blood pressure
   Portapres model 2.0

Analysis by hierarchical mixed regression
Effects are significant for p<0.05

Fixed effects
- G_z at heart
- Tilt angle
- Action (one foot, two feet, or stepping)

Dependent variables
- Calf volume
- Heart rate
- Systolic and diastolic blood pressure
Results: calf volume

Significant effect of $G_z$ (all actions tested separately)  
$p<0.001$

Significant effect of action  
$p<0.001$

$n=14$, average ± SE. Average between seconds 40-45 of the start of each action

Results: heart rate response

Significant effect of $G_z$ ($p<0.001$ two feet, $p=0.003$ stepping)  

Significant effect of tilt when standing on both feet ($p<0.001$)

$n=16$, average ± SE. Average of the last half of action time period (30 or 60s)
Results: blood pressure response

Significant effect of $G_z$ (p<0.001) for standing on both feet and for stepping in place

*Tilt angle effects were inconsistent*

Blood pressure, heart level (standing on both feet)  
Blood pressure, heart level (stepping in place)

---

General discussion

1. Calf volume, heart rate, blood pressure
   - Increase significantly with increasing $G_z$ at heart
     - Decrease in venous return due to blood shift towards the legs
     - Decreased pressure at the baroreceptors
   - Increase significantly with increasing $g$-gradient (calf volume, HR)
     - Generally due to the fact that $G_z$ was higher at the feet for higher $g$-gradients

2. Exercise (stepping in place) reduces the effects seen above
   - Activation of the muscles reduces the orthostatic challenge
     - Decreased calf volume $\rightarrow$ increased blood return to heart $\rightarrow$ less compensatory response needed
Implications of Experiment 1

*Short- vs. large-radius centrifugation*

Low g-gradient $\rightarrow$ large radius
High g-gradient $\rightarrow$ short radius

Based on our study
- Short-radius centrifugation results in elevated HR and BP responses
  Hastreiter and Young 1997, Calero et al 2004
  With high enough $G_x$-levels, this could become problematic
  $G_x$-tolerance: Miller et al 1971, Burton and Meeker 1992
- Exercise helps subjects to tolerate higher $G_z$ and g-gradients, and may even be necessary
  Higher $G_z$-tolerance: Wiese et al 2003

---

Experiment 2: Effectiveness of stair-stepping during centrifugation

MIT Short-Radius Centrifuge
Motivation and hypothesis

1. Exercise (cycling) on a centrifuge is effective in preventing bedrest deconditioning.
2. Upright exercise is effective in improving fitness in periods as little as four to eight weeks.

Hypothesis

For healthy, sedentary subjects, an eight week exercise program (stair-stepping, resistive arm bands) on a centrifuge will:
- Improve aerobic capacity and endurance
- Increase muscle strength
- Improve body composition
- Have no negative side effects
**Exercise sessions**

Centrifuge spins at 30 RPM (1.6-1.8-G, at the feet, ~0.4-G at the heart)

Subject exercises (20-40 minutes) at a target heart rate

Measurements during exercise:
- Foot forces
- Work rate

Statistical analysis of measurements

Analysis by repeated measures general linear model (repeated over weeks 0, 4, and 8)

Hypothesis testing (contrast between weeks) was performed for measures that could be fit under the general linear model

**Measurements**

- **Aerobic**
  - Treadmill VO2-max (MVL)
  - Upright stepping test (MVL)
  - Resting energy expenditure (CRC)
  - Cycle ergometer VO2-max (ZC)
- **Strength**
  - Quadriceps maximum force extension (MVL)
  - Pushups test (ZC)
- **Body composition**
  - Leg circumferences (MVL)
  - Full body dual x-ray absorptiometry (DXA) scan (CRC)
  - Skinfold and circumference tests (ZC, CRC)
- **Other**
  - Sharpened Romberg test (MVL)
  - Orthostatic stand test (CRC)
  - Sit-and-reach flexibility (ZC)

MVL = Man-Vehicle Laboratory, ZC = Z-Center, CRC = Clinical Research Center
Sessions' results

- Nine male subjects started, one dropped out after four weeks
- No motion sickness reported
- Peak foot forces on average 83% body weight

Results: aerobic fitness
Upright stepping test

Stepping cadence at constant heart rate

Maximum number of steps in two minutes

$p=0.017$

$n=9$

$p=0.001$

$n=9$
Results: strength and body composition

**DXA scan**
- Leg fat percentage: 4.0-4.3% decrease (p=0.046)
- Pelvic bone mineral content: 2.9% increase (p=0.040, weeks 4 to 8)

Results: all measurements

<table>
<thead>
<tr>
<th>Category</th>
<th>Measurement</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic</td>
<td>Treadmill VO2-max (MVL)</td>
<td>Significant changes</td>
</tr>
<tr>
<td></td>
<td>Upright stepping test (MVL)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resting energy expenditure (CRC)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cycle ergometer VO2-max (ZC)</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>Quadriceps maximum force extension (MVL)</td>
<td>Increase, weeks 0 to 4 to 8 (NS)</td>
</tr>
<tr>
<td></td>
<td>Pushups test (ZC)</td>
<td>Significant changes</td>
</tr>
<tr>
<td>Body composition</td>
<td>Leg circumferences (MVL)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full body dual x-ray absorptiometry scan (DXA) (CRC)</td>
<td>Significant changes</td>
</tr>
<tr>
<td></td>
<td>Skinfold and circumference tests (ZC, CRC)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Sharpened Romberg (balance) (MVL)</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>Orthostatic stand test (CRC)</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>Sit-and-reach flexibility (ZC)</td>
<td>Increase, weeks 0 to 4 to 8 (NS)</td>
</tr>
</tbody>
</table>

MVL = Man-Vehicle Laboratory, ZC = Z-Center, CRC = Clinical Research Center
General discussion

- Eight out of nine subjects were able to tolerate eight weeks of centrifuge exercise
  - No negative side effects (e.g. balance)

- Fitness benefits were seen for aerobic, strength, and body composition measurements

- Aerobic fitness benefits were mostly limited to the upright stepping test
  - Indicates exercise specificity (testing in the same mode that you train)

- Longer protocol would have resulted in significant differences in more measurements

Centrifuge exercise is consistent with upright exercise

No upright controls – so we can not say “this exercise is as effective as upright”

**Experiment 2 findings**

- Greater work rate at a constant heart rate after eight weeks
- Increase in number of pushups, quadriceps extension force after eight weeks
- Increase in number of steps done in two minutes

**Existing literature**

- Lower heart rate for a given work rate after eight weeks (cycling, upright) (Clausen et al 1970, Sugawara et al 2001)
- Four week run/walk exercise program resulted in an increase in skeletal muscle protein turnover (Pikosky et al 2006)
- Four week run/walk exercise program resulted in a significant decrease in timed run trial (Pikosky et al 2006)
**Implications of Experiment 2**

*Stair-stepping as an exercise modality*

- Foot forces higher than cycling, not as high as walking
  - May help with bone maintenance
  - Higher foot forces with external loading, faster centrifugation

- Neuromuscular coordination
  (Kandel et al 2000, ch. 37)
  - "Practice" walking while weightless
  - Forward stroke would be better

---

**Summary of thesis work**

*Artificial gravity combined with exercise as a countermeasure to spaceflight deconditioning*

Two experiments

- Exercise attenuates physiological responses to high g-gradients
- Stair-stepping is an effective exercise modality on a short-radius centrifuge
Recommendations

Centrifuge exercise as a spaceflight countermeasure

1. Exercise should be combined with short-radius centrifugation because it allows for tolerance of higher G_x and higher g-gradients (particularly true for astronauts who are already deconditioned)

2. Artificial gravity should be considered as a force background for space exercise, instead of using external loading

3. Stair-stepping or similar exercise should be considered for use on a centrifuge

4. Based on these results, centrifuge exercise may be a highly effective countermeasure to long-duration spaceflight deconditioning

Acknowledgements

Thesis defense committee: Larry Young, Thomas Jarchow, Roger Mark, Lars Oddsson, Erika Wagner, and Paul DiZio

Experimental subjects
MVL faculty and staff: Dava Newman, Chuck Oman, Jeff Hoffman, Alan Natapoff, and Liz Zotos

MVL students and UROPS

Funding sources
NASA/Johnson Cooperative Agreement # NNJ04H103A
NASA International Multi-Disciplinary Bedrest Study, grant # NNJ04HD64G
NASA GSHP grant # NNX06AH21H
Zonta International Amelia Earhart Fellowship
AAIA John Leland Atwood Fellowship
EXERCISE PROTOCOLS DURING SHORT-RADIUS CENTRIFUGATION FOR ARTIFICIAL GRAVITY

BACK UP SLIDES

Background Experiment 1 Experiment 2 Conclusion

Publications

Peer-reviewed journals

- J.L. Edmonds, P.F. Migeotte, R. Vanspaumen, F. Wuyts, T. Jarchow, L. R. Young. Light exercise mitigates the cardiovascular effects induced by gravity gradients generated on a short radius centrifuge. To be submitted summer 2008.

Presentations, abstracts, and posters


37/36
APPENDIX F: THESIS DEFENSE SLIDES

Space flight deconditioning
Cardiovascular

- Headward fluid shift results in:
  - Decrease in blood volume
  - Decrease in blood pressure and heart rate
  - Slow autonomic responses

Low Pressure

<table>
<thead>
<tr>
<th>Background</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Conclusion</th>
</tr>
</thead>
</table>

Constant pressure

<table>
<thead>
<tr>
<th>Background</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Conclusion</th>
</tr>
</thead>
</table>

High Pressure

Heart rate response to flight

Simlar responses for blood pressure

Figs. 3a and 3b adapted from J.R. Rowell (1985).
Space flight deconditioning
Cardiovascular

Orthostatic intolerance upon return to gravity
- Overall around 20% experience orthostatic intolerance (worse for women, worse for longer flights)
  
  * (MacK et al. 2001, Waters et al. 2002)

- Slower, and elevated, heart rate response to standing after flight. Inadequate blood pressure compensation

G-gradient implication: change in centrifuge radius

Centrifuge radius of tilting ESA centrifuge = 2.3
Example case of 1.0 g at the heart

<table>
<thead>
<tr>
<th>Tilt</th>
<th>G-gradient*</th>
<th>Radius of equivalent non-tilting centrifuge</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>77%</td>
<td>2.3 m (at 32 RPM)</td>
</tr>
<tr>
<td>21</td>
<td>57%</td>
<td>3.0 m (at 23 RPM)</td>
</tr>
<tr>
<td>45</td>
<td>24%</td>
<td>7.1 m (at 12 RPM)</td>
</tr>
</tbody>
</table>

* $g_{	ext{foot}} = g_{	ext{head}}g_{	ext{foot}}$
Implication of the gravity gradient: change in centrifuge radius

Example case of 1.0-g at the heart

\[ G\text{-gradient} = \frac{(g_{\text{vert}} - g_{\text{inert}})}{g_{\text{vert}}} \times 100 \]

- For constant radius, tilt angle \(\uparrow\) g-gradient
- Radius of a non-tilting centrifuge, to achieve the same g-gradient

G-levels and tilt angles (g-gradients)

- 0 deg: 76-77% gradient
- 21 deg: 48-61% gradient
- 45 deg: 0-30% gradient

\[ \downarrow\text{tilt angle} \rightarrow \uparrow\text{g-gradient} \]
**Comparison of centrifuge exercise methods**

<table>
<thead>
<tr>
<th>Aerobic</th>
<th>Cycling</th>
<th>Stair-stepping</th>
<th>Squats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Bone</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>maintenance</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Coriolis deflections</td>
<td>Poor</td>
<td>Fair</td>
<td>Fair</td>
</tr>
</tbody>
</table>

(From supine on centrifuge)

**Recommendations**

*Future Earth-based studies*

*Responses to a g-gradient (Experiment 1)*
1. Spin to higher g-levels. Does exercise prevent presyncope?
2. Control net g-level rather than g-level at the heart

*Long-term exercise protocols (Experiment 2)*
1. Extend from 8 weeks to 16 weeks
2. Use an upright control group
3. Include females (must have more subjects)