

# SCALES MODIFIED FOR USE ON BOARD THE HUMAN CENTRIFUGE IN THE MIT MAN VEHICLE LAB

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

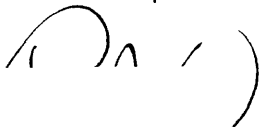
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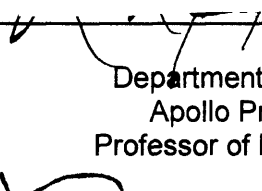
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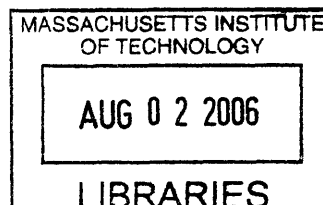
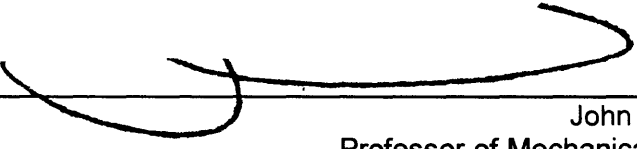
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# **SCALES MODIFIED FOR USE ON BOARD THE HUMAN CENTRIFUGE IN THE MIT MAN VEHICLE LAB**

By

**Heather Marie Samuelson**

Submitted to the Department of Mechanical Engineering  
on May 10, 2006 in partial fulfillment of the  
requirements for the Degree of Bachelor of Science in  
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## **ABSTRACT**

The MIT Man Vehicle Lab (MVL) is currently performing research on the effects of rotational artificial gravity on humans through the use of a short-radius centrifuge. The MVL centrifuge allows subjects to spin in the supine position with their heads at the center of rotation and their feet facing outwards. To collect information regarding actual forces experienced by a subject while on the centrifuge, a set of scales was designed specifically to measure the equivalent of the human body's weight in artificial gravity. These were mounted on board a stair stepper exercise device to measure the forces exerted at the feet of subjects while exercising. Exercise is particularly important in preventing microgravity-induced deconditioning of the body and without exercise a deconditioned subject might not be able to withstand the stress of experiencing artificial gravity. The primary focus of the research is to gain a better understanding of the overall effects resulting from artificial gravity on humans and eventually to alleviate undesirable ones.

The Contek WCS-20® bathroom scale was redesigned to fit on board the stair stepper device on the centrifuge and to safely and securely measure the forces exerted by each foot of a subject while exercising. It was also modified to give continuous force readouts; measurements were made while a subject was performing simple exercises on a stair stepper device in artificial gravity. The subject was spun at 0, 12.5, 23 and 30 rpm on the centrifuge and force measurements were taken at each speed. The forces from the two scales (left foot and right foot) sum to give the subject's total equivalent weight at each rotational speed. In addition, the forces exerted radially by the subject vary as he altered his body's distance from the center of the centrifuge through the series of exercises. These scales can be used to provide foot force data and, from this, a better understanding can be gained of the overall effects of artificial gravity on the human body

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## **INTRODUCTION**

The MIT Man Vehicle Lab (MVL) is currently performing research on the effects of rotational artificial gravity on humans through the use of a centrifuge. The primary focus of the research is to gain a better understanding of the overall effects resulting from artificial gravity and eventually to alleviate undesirable ones. Research is currently being performed to determine the duration of time and level of rotation that are optimal for reducing the effects of microgravity on the human body [1].

Although a model for the force experienced by a human on board the centrifuge exists, it is based on several assumptions. It is assumed that a human is composed of a spherical head, a rectangular box for a torso and cylindrical limbs [2]. As there is a large amount of variation between people and no one has this idealized body shape, it is valuable to collect information regarding actual forces experienced by a subject while on the centrifuge. The redesigned scales will provide this data in order to better determine what the effects of artificial rotational gravity are on humans.

## **APPLICATIONS OF ARTIFICIAL GRAVITY**

Artificial gravity, with its production of radial accelerations, is currently being examined as a promising countermeasure against the deleterious effects experienced by astronauts in the microgravity environment of space [3]. During the course of numerous space missions, data has been generated indicating that when astronauts are exposed for extended periods of time to a microgravity environment they experience significantly debilitating physiological side effects. These changes include the degradation of skeletal and cardiovascular muscles, a loss of bone density and deconditioning of neurovestibular reflexes as the human body attempts to adapt itself to its new environment [4-7]. Although placing a human body under the influence of radial forces from a centrifuge may stave off some of the side effects of space travel, the full effects of artificial gravity by centrifugation on humans are not yet completely understood.

One area which is currently being examined in detail is the effect of combining centrifugation with exercise to prevent microgravity-induced deconditioning of the body. Several options currently exist to slow the degradation of the musculoskeletal and cardiovascular systems in the microgravity environment of space including exercise, lower-body negative pressure devices, fluid loading before reentry and pharmacologic

interventions; however, little is understood about the combination of any of these with an artificial gravity environment [7-13]. In addition, without exercise a deconditioned subject might not be able to withstand the stress of centrifugation. In order to better understand how the human body responds to exercise while rotating, the forces exerted by the feet of a subject on a set of electronic scales were measured.

# BACKGROUND

## EQUATIONS

Force exerted outwards on the centrifuge can be calculated from the equation  $F = mr\omega^2$ , where  $m$  is the mass of the subject,  $r$  is the distance from the center of the centrifuge to the center of mass of the subject and  $\omega$  is the velocity at which the bed rotates. The forces exerted at the feet of a still subject should therefore increase as the velocity of the centrifuge increases. Also, as the subject alters his body's distance from the center of the centrifuge, the forces exerted at the feet will change. Different distances from the center of the centrifuge experience different outward forces which increase farther out on the centrifuge. This allows each of the different body segment masses to experience different forces.

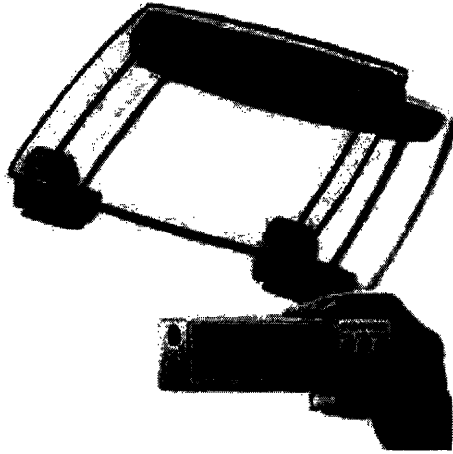
From the Body Mass Index (BMI) calculator, the average weights and heights of people are given. For each height, an average weight was determined by averaging the minimum and the maximum heights of subjects in the range. There is a minor disconnect in the graph between 61 and 62 inches and between 72 and 73 inches. This occurs because average heights for women and men overlap in the area between 62 and 72 inches; however, for values below 62 inches only women's weights were taken into account and for values over 72 inches only men's weights were taken into account. See Appendix A, Table 5 on page 39 for height and weight values.

## CONTEK WCS-20®<sup>1</sup>

The Contek WCS-20® will be used as a model scale and will then be modified to fit on board the stair stepper device to measure forces exerted by a subject. The scale cannot be used as it is because it was not designed to be used on board a centrifuge. The necessary modifications are described below. The Contek-WCS 20® is a 12" x 12" x 2" bathroom scale with a ¼" tempered glass platform and a weight capacity of 300 lbs [14]. See Figure 1 on page 14.

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<sup>1</sup> Contek WCS-20 is a brand name and is trademarked.



**Figure 1: Original WCS-20 scale from Contek® [15].**

For our purposes, several modifications to the original scales were necessary: they were condensed down to a smaller size, they were covered with new footplates and they received new circuits and wiring. Two scales moving parallel to one another are necessary in order to measure a subject's output from both feet. Since the non-modified scales are so large, they would need to be placed far enough apart to allow for their individual motions. This distance is not comfortable for a subject to use while exercising.

In addition, the base plate of the scale is made of glass. For use on board the rotating centrifuge, a more robust material is needed for the base of the scale. The scale is also equipped with an on/off switch and after several seconds of inactivity turns itself off. This automatic shut-down cannot be allowed to occur on board the centrifuge because the only way to turn the scale back on again if this were to occur would be: to stop the centrifuge and the experiment, to allow the centrifuge to spin down, (which takes quite some time due to its large momentum), and then to turn the scale back on, and to begin the experiment again.

Although the Contek WCS-20® has the ability to wirelessly transmit in a range up to 40 feet, other nearby electrical appliances of a similar frequency have the potential to cause interference [16]. In addition, two separate outputs will be simultaneously transmitted from the centrifuge and will need to be received separately by the correct receiver. Each scale works best while it is directly facing its own receiver. The centrifuge will not necessarily always be pointed directly at the receivers at the beginning of an experiment and certainly will not face the receivers while rotating during an experiment. In order to be mounted on the centrifuge, the scales need to be mounted

vertically instead of horizontally, as the forces exerted by a subject while exercising are in the radial direction. The receivers would have to be mounted in a horizontal plane and thus, the scales would never face the receivers.

Additionally, the scale integrates information from all four foot plates in order to give one output which is wirelessly transmitted from the base to the receiver [16]. One main reason for choosing the Contek WCS-20® was so that this one output could be obtained for each foot and transmitted through the slip ring. Due to the differences between the original intent of the scales and our intent for them, we simplified the scale so that certain unnecessary functions were eliminated: the regulation of the on/off switch, the ability of the scales to wirelessly transmit, the weight storage function and the ability of the scales to measure the weight of a baby.





# METHODS

## MODELING

As was suggested by Diamandis in 1988 the model idealized person of a height of 160 cm has a spherical head diameter of 20 cm, arm lengths of 65 cm, a torso length of 50 cm and leg lengths of 90 cm [2]. These dimensions scale upwards as the height of a person increases. The ratio of length of each body segment over the total body length for the head is 0.06, for the arms is 0.36, for the torso is 0.31 and for the legs is 0.73. These ratios can be multiplied by the total height of a subject to calculate the lengths of each body segment for subjects of various heights. Additionally, equivalent weight fractions were calculated for each body segment. The equivalent weight fraction for the head was 0.05, for the arms was 0.13, for the torso was 0.37 and for the legs was 0.45.

Three distinct models based on real humans were generated. In the first modeling situation the subject was weighed. His predicted height was calculated from a linear regression of the BMI calculator. The weights and corresponding heights of both male and females were plotted and through Excel®, and a best fit line was generated for the data [17]. The equation of the line in inch/pound units was  $x = 0.2845y + 25.778$  [17]. See Appendix A, Figure 27 on page 39 for height and weight values of humans. Using this regression, the height of the subject was calculated from the weight. The height in inches was converted to a height in feet. The weight in pounds was converted to a mass by dividing by  $g$ , where  $g = 32.2 \text{ ft/s}^2$  [17]. The body segment length ratios were multiplied by the subject's predicted height to determine the expected lengths of each segment and thus the "r" value for radial acceleration of each of these body segments [17]. Since the segments were symmetrical, the geometric center was also the center of mass [17]. For the head, this entailed dividing the diameter by 2. For the torso, the length was divided by 2 and added to the total value of the head. The arms were calculated in a similar manner. The legs were calculated by dividing the leg length by 2 and adding it to the total length of the torso and head.

The equivalent weight fractions were multiplied by the total mass of the subject to give the mass fractions of the corresponding body parts. The mass fractions were multiplied by their corresponding length fraction for each of the body segments, as described above. These values were summed and then multiplied by  $\omega^2$ . At 23 rpm,  $\omega = 2.41$ . At 30 rpm,  $\omega = 3.14$ . This calculation provided one value for  $m * r * \omega^2$ , equaling

the force exerted at the feet of a supine subject. The overall equation is  $(m_{\text{head}} * r_{\text{head}} + m_{\text{torso}} * r_{\text{torso}} + m_{\text{arms}} * r_{\text{arms}} + m_{\text{legs}} * r_{\text{legs}}) * w^2$  [17].

In the second modeling scenario, both the weight and height were measured from the subject. The same process was followed to calculate the forces felt by the subject at his feet; however, the true value of the height was inserted in place of the calculated value as the basis for the calculations.

In the third modeling scenario, the weight and height of a subject were again measured. In addition, the lengths of each of the subject's body segments were measured. Calculations were performed in a similar manner to those in the first two scenarios. See Appendix B for all modeling calculations.

## CONSTRUCTION

To obtain actual measurements of the forces exerted by each foot, the equivalent of a mini-scale was necessary. Two identical devices were created from modified Contek scales to safely and securely fit on board the human centrifuge and measure the forces exerted by each foot of a subject while exercising.

The force sensor boxes were used without modification from the original product. See below Figure 2, Figure 3, Figure 4 and Figure 5 for pictures of the original foot plates.

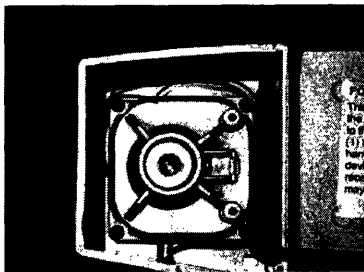


Figure 2: Upper left foot plate.

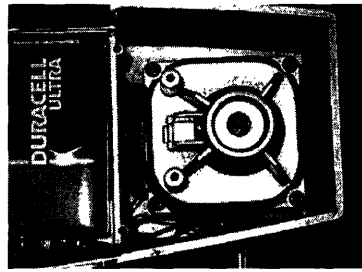


Figure 3: Upper right foot plate.

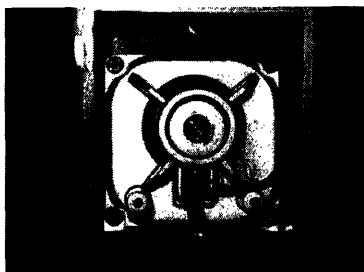


Figure 4: Lower left foot plate.

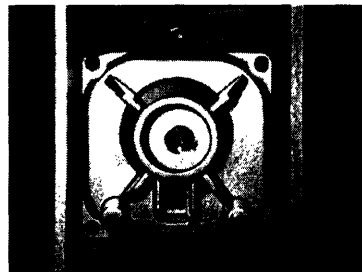
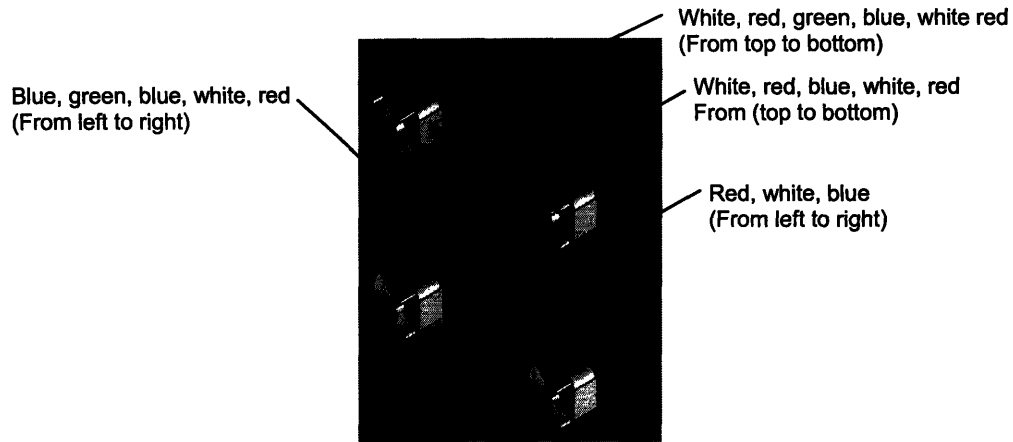


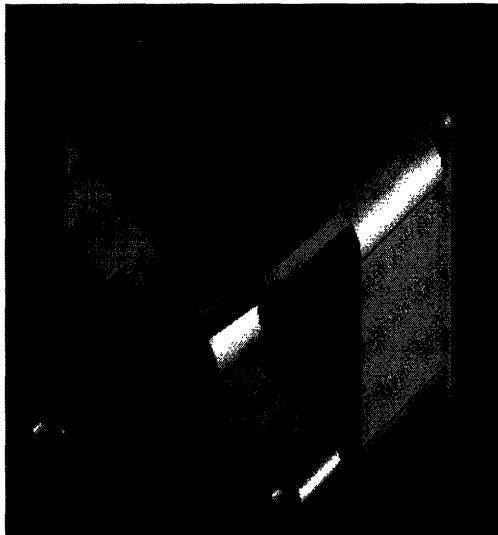
Figure 5: Lower right foot plate.

To place them on a smaller, more robust backing, the wiring needed to be cut apart and soldered together again. Each of the four force sensor boxes, located in the corners of the original scale, were firmly affixed to the tempered glass platform. These were removed by melting the adhesive with a heat gun. See Figure 6 for positions of the original foot plates on the glass backing.

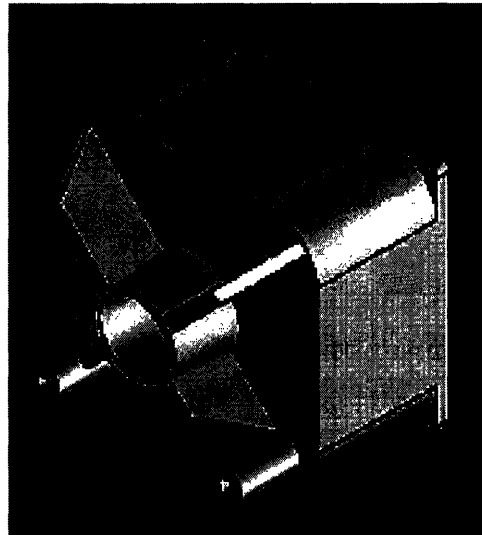


**Figure 6: Original positions of foot plates on backing with indicated wire colors.**

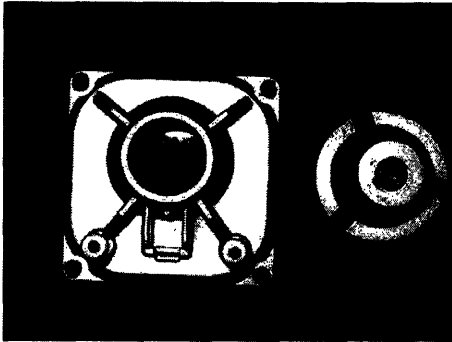
Once the force sensors were cooled and detached from the glass, they then needed to be separated from one another. Thin pieces of aluminum with a plastic mapping of the wires between them connected each of the foot plates on the right and on the left. Inside each of the foot plates, the ends of the aluminum were bent to hold it securely in place. The aluminum pieces were straightened and removed from the force sensor boxes. See Figure 7, Figure 8, Figure 9 and Figure 10 below and on page 21 for views of the foot plate components.



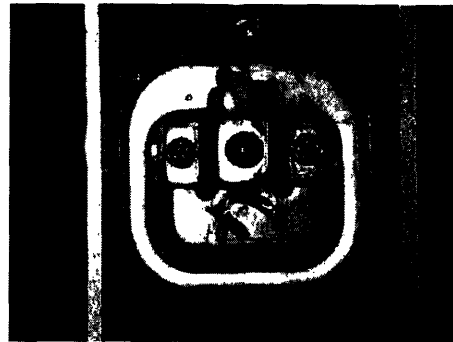
**Figure 7: Complete foot plate.**



**Figure 8: Plastic cover minus foot.**

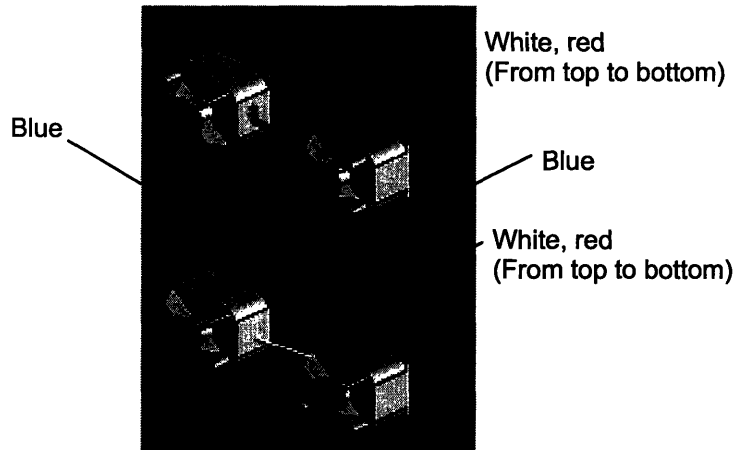


**Figure 9: Plastic cover with internal piece.**



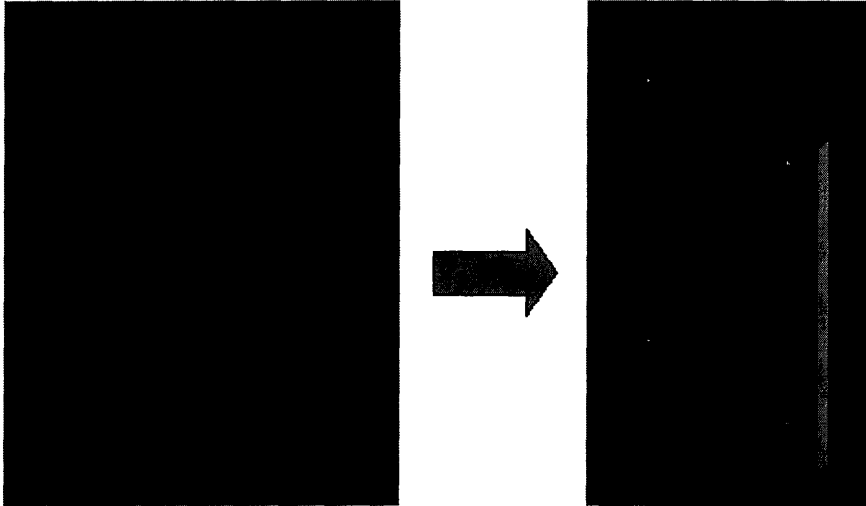
**Figure 10: Uncovered force sensor.**

The wires coming from the foot plates initially led into a large circuit that had many functions which were not required for this experiment; thus, the circuit itself was simplified greatly so that its only purpose was to integrate the information from the four feet. See Appendix C, Figure 28 on page 43 for more information on the schematic of the circuit and explanation of its modified functionality. In addition, the wiring was modified to accommodate the new dimensions of the foot plate. See below Figure 11 for modifications to the wiring on the scale.

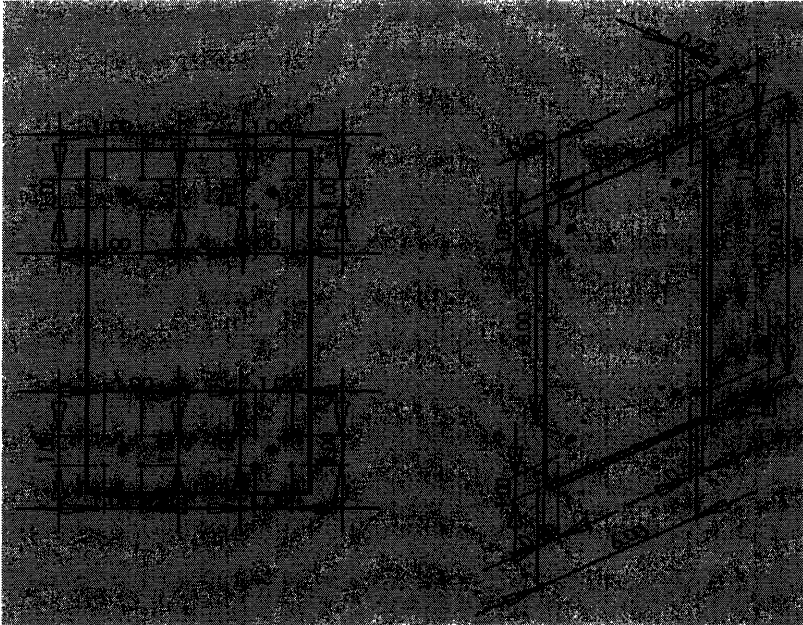


**Figure 11: Modified wiring.**

Each of the force sensor boxes and the circuit were mounted on a 12" x 6" x 1/4" piece of aluminum. The backing was constructed to be a size that allowed the subjects to comfortably exercise with one foot on each mini-scale. Hole were drilled through the backing and tapped. See below Figure 12 and Figure 13 for views of the modified base plate and dimensions.

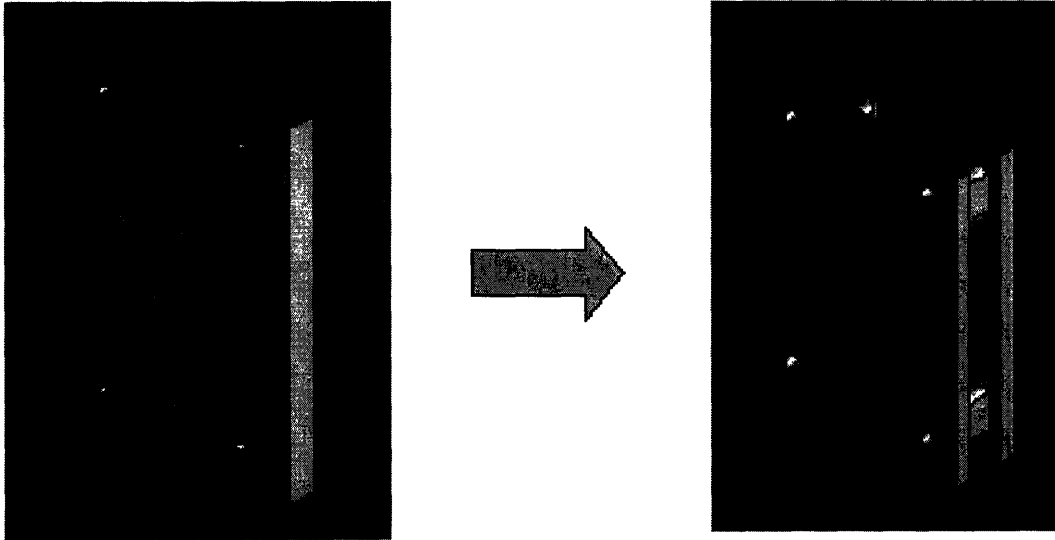


**Figure 12: The modified base plate.**

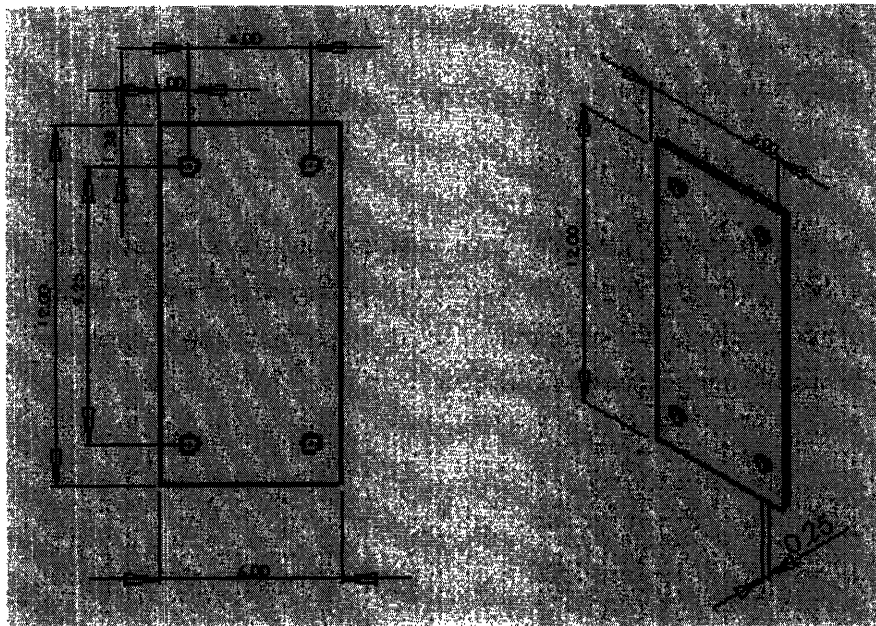


**Figure 13: Dimensions of the modified base plate.**

A screw was used to hold in place each force sensor box. On the other side, another 12" x 6" x 1/4" piece of aluminum was used. It was drilled and tapped in each of the four corners where the centers of the force sensor boxes were located. See below Figure 14 and Figure 15 for views of the additional top plate and dimensions.

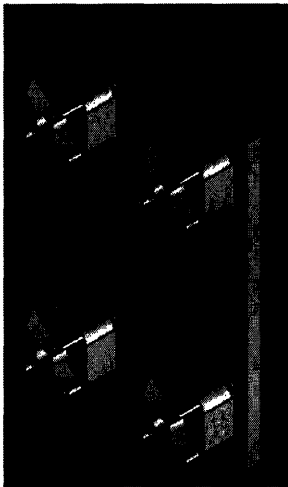


**Figure 14: Addition of the top plate.**

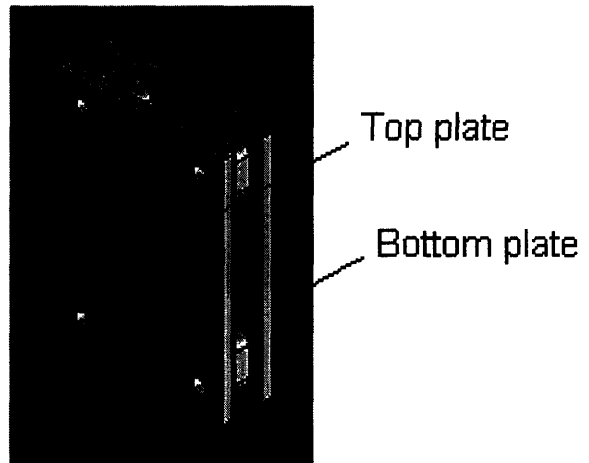


**Figure 15: Dimensions of the top plate.**

After the foot plates were attached to the bottom plate, the top plate was mounted as follows. A bolt was placed through each of the four holes, and each bolt was tightened by the same number of quarter turns of a screwdriver. This allowed the pressure to be exerted equally on each of the foot plates when a subject pressed on the scale, rather than having one corner of the scale preferentially sense more equivalent weight. The miniature scales were determined to have the ability to measure the range of forces exerted by a subject while exercising in a rotating environment. See below Figure 16 and Figure 17 for views of the mounted foot plates and completed scale.



**Figure 16: Foot plates mounted on base.**



**Figure 17: Completed force plates.**

The two scales were mounted vertically on a stair stepper device which has already been in use on board the centrifuge. The subject exercised while in the supine position. On the bed of the centrifuge is a slider that allowed the subject to slide easily in and out from the center of the centrifuge while exercising.



## **EVALUATION**

The scales were calibrated by placing them flat on the floor and adding 200 pounds of weights. The voltage out was adjusted so that it was approximately 7 volts [17]. The 200 pounds of weight was removed in five pound increments while the voltage out was monitored. The voltage out is scaled down from the weight of a subject in pounds by a factor of 29.24 [17].

One set of measurements which was gathered examined the forces that are exerted outwards by the feet of a subject while performing simple exercises on the stair stepper device in artificial gravity. A subject was spun at various speeds on the centrifuge and force measurements were taken at each speed. The subject was a 6 foot tall male and weighed 174 pounds.

The subject was initially still on the centrifuge for ten minutes, then was spun up to 12.5 rpm, 23 rpm and 30 rpm while remaining still. At each speed the forces exerted by the subject were recorded for ten minutes. The subject was then asked to perform stair stepping exercise at his own pace for a two minute interval. The first minute was not counted for data, but allowed the subject to become accustomed to exercising on the centrifuge. Data was gathered during the second minute. This procedure was repeated at each of the four measured speeds of the centrifuge, at decreasing speeds from 30 rpm to 0 rpm. See Appendix D for additional information regarding the protocol for the experiment. See Appendix E for the informed consent.



## RESULTS

The forces from the two scales sum to give the subject's total equivalent weight at each rotational speed and were compared to the equivalent weights predicted by each of the three modeling situations. In addition, the forces exerted outwards by the subject varied as he altered his body's distance from the center of the centrifuge through the series of exercises.

At 0 rpm the forces exerted by the subject outwards were approximately zero. When a 174 lb. subject was spun up to 12.5 rpm, or approximately 0.3 g at the feet, his equivalent weight increased to approximately 25 lbs. By 23 rpm, the subject was experiencing approximately 1 g at his feet and weighed approximately 103 lbs. By 30 rpm, or approximately 1.7 g at the feet, the subject weighed approximately 204 lbs. These equivalent weights increase monotonically as expected. See below Figure 18 for the resting equivalent weight of the subject from 0 rpm to 30 rpm.

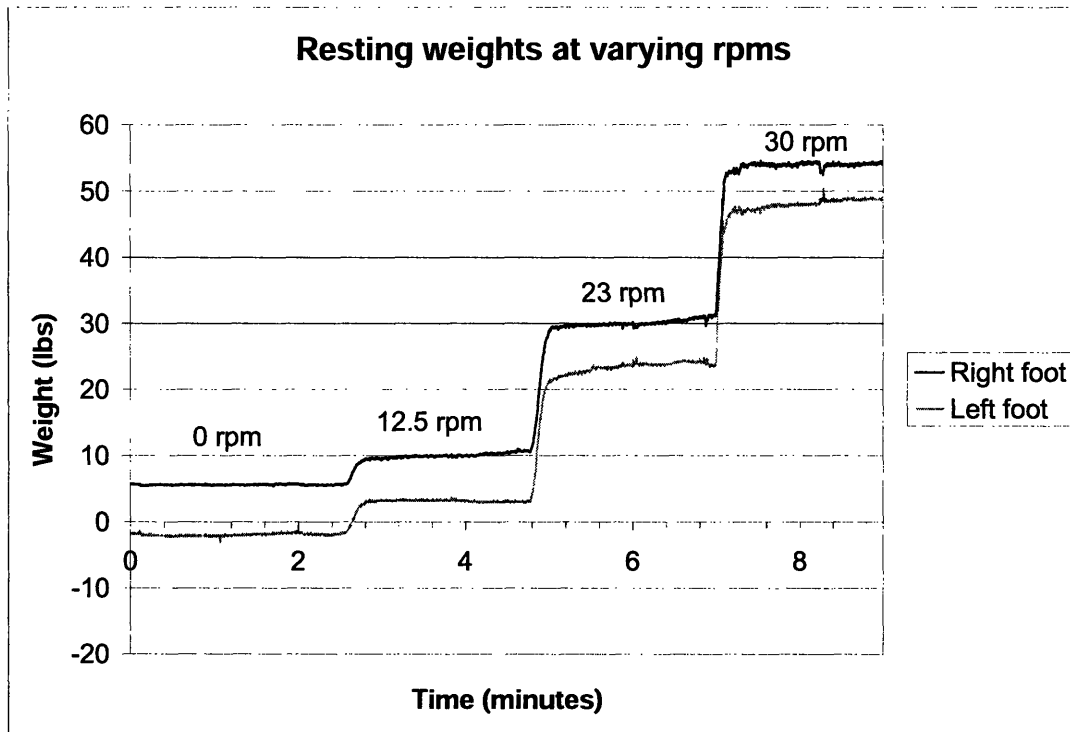


Figure 18: Resting equivalent weights at 0, 12.5, 23 and 30 rpm of a 174 lb. subject.

The equivalent weights of the subject were measured as the subject performed a series of bends and steps. Typically by this time, the subject's feet were pressing unevenly on the scales; however, his total weight remained unchanged. As is shown in Figure 19, as the subject stepped, the equivalent weight increased on one foot and decreased accordingly on the other.

**Table 1: Average equivalent weight by foot of a 174 lb. subject in pounds**

		Right Average	Left Average
0	Bending	3.14	-3.81
	Stepping	71.33	61.91
12	Bending	17.64	10.03
	Stepping	84.00	95.51
23	Bending	60.39	57.01
	Stepping	148.36	150.13
30	Bending	89.67	88.07
	Stepping	158.01	124.63

**Table 2: Average equivalent weight in pounds of a 174 lb. subject**

0 rpm	Stepping	35.49
	Bending	-4.90
	Still	3.66
12.5 rpm	Stepping	42.73
	Bending	19.26
	Still	12.73
23 rpm	Stepping	92.71
	Bending	94.65
	Still	51.31
30 rpm	Stepping	103.11
	Bending	118.08
	Still	101.94

The subject demonstrated that his equivalent weight remained reasonably constant while he was motionless on the scales. While he was performing the knee bending experiments; however, his equivalent weight varied depending on his distance from the center of the centrifuge. This is evidenced in the difference between the stationary equivalent weight in Figure 18 on page 27 to the equivalent weight of a subject in Figure 20 on page 29, Figure 22 on page 30, Figure 24 on page 31 and Figure 26 on page 32 while performing bending motions. See above Table 1 for average equivalent weight by foot and Table 2 for average total equivalent weight while exercising.

### 30 RPM

The average equivalent weight of the subject while in the knee bend position at 30 rpm was 118.08 lb. whereas the average equivalent weight of the subject with his legs straight at 30 rpm was 101.94 lbs. See below Figure 19 for the stepping profile and Figure 20 for the bending profile at 30 rpm.

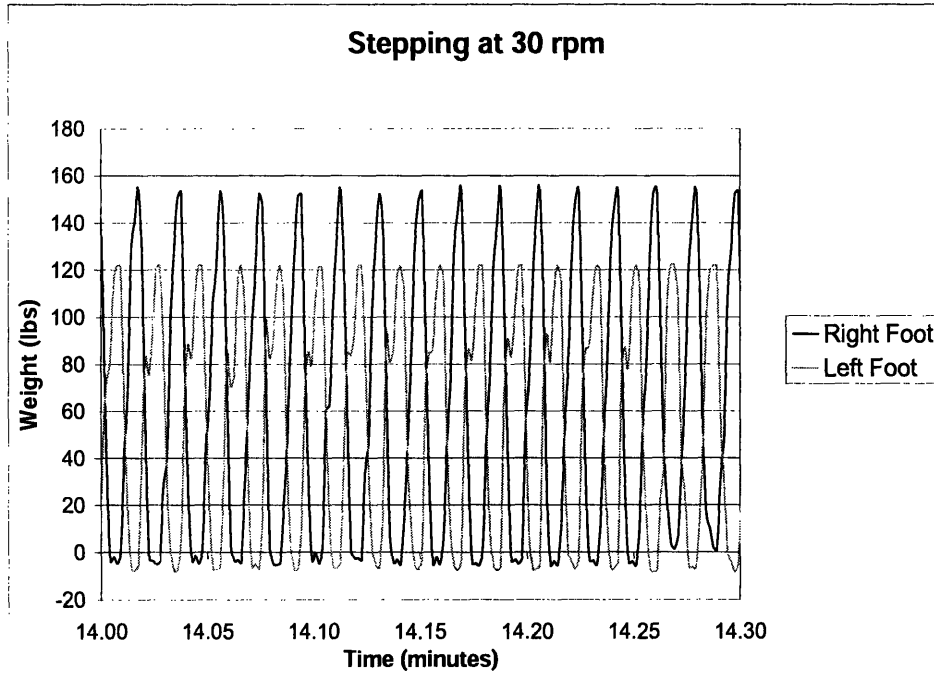


Figure 19: Stepping profile at 30 rpm.

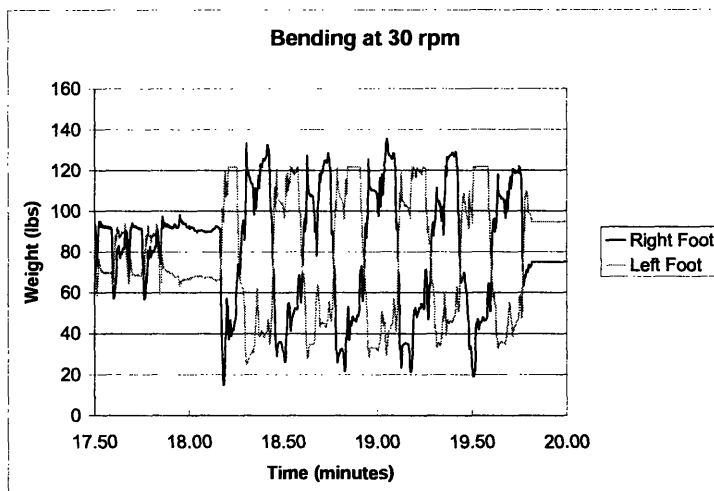


Figure 20: Force profile during knee bends at 30 rpm.

## 23 RPM

The average equivalent weight of the subject while in the knee bend position at 23 rpm was 94.65 lb. whereas the average equivalent weight of the subject remaining motionless at 23 rpm was 51.31 lbs. See below Figure 21 for the stepping profile and Figure 22 for the bending profile at 23 rpm.

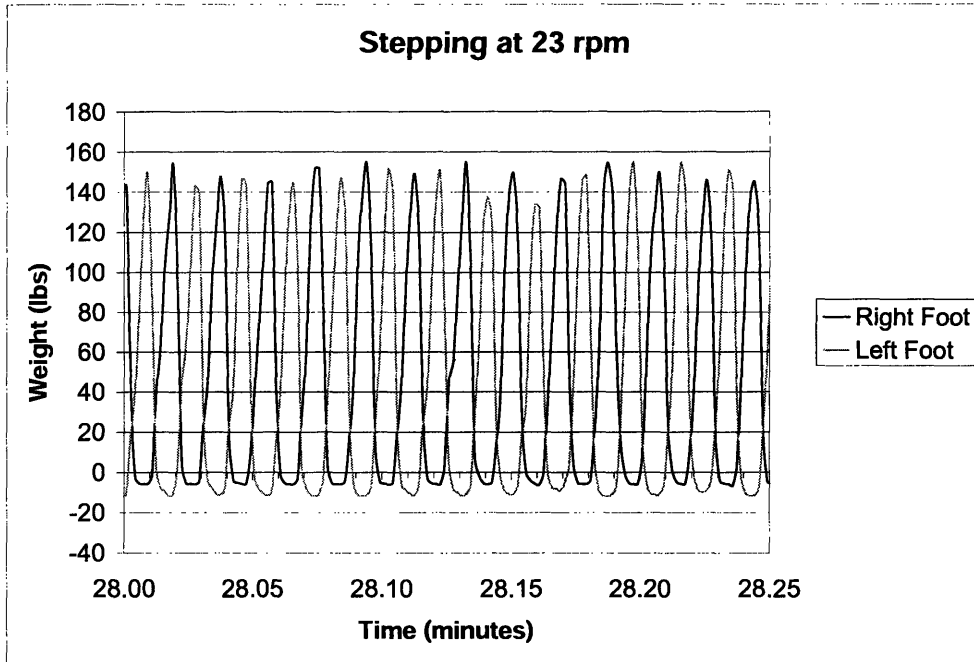


Figure 21: Stepping profile at 23 rpm.

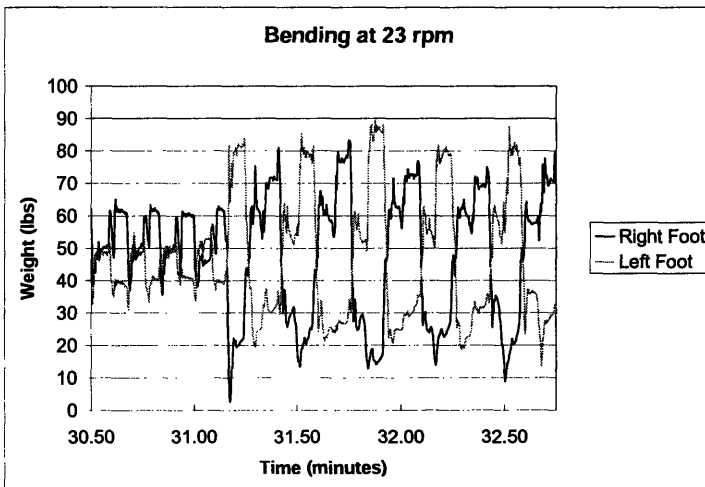


Figure 22: Force profile during knee bends at 23 rpm.

## 12.5 RPM

The average equivalent weight of the subject while in the knee bend position at 12.5 rpm was 19.26 lb. whereas the average equivalent weight of the subject remaining motionless at 12.5 rpm was 12.73 lbs. See below Figure 23 for the stepping profile and Figure 24 for the bending profile at 12.5 rpm.

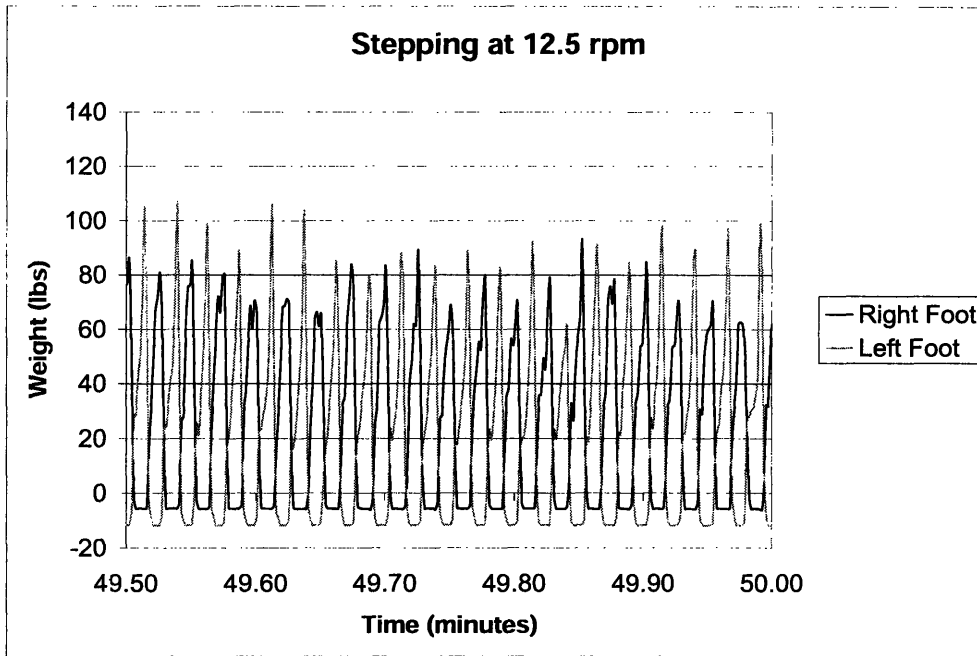


Figure 23: Stepping profile at 12.5 rpm.

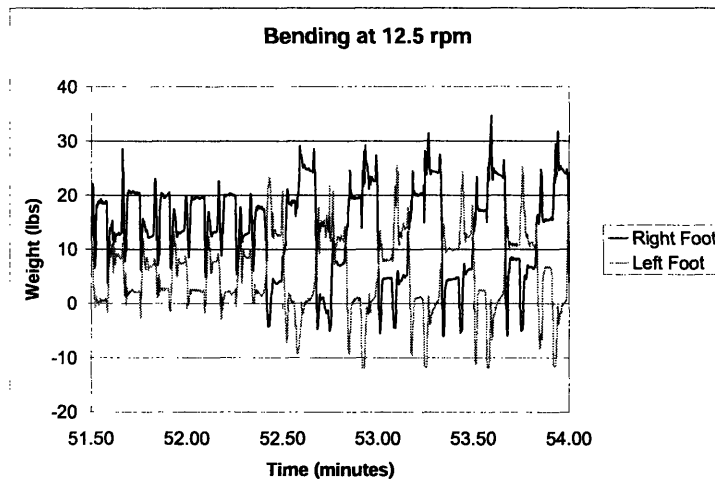


Figure 24: Force profile during knee bends at 12.5 rpm.

## 0 RPM

The average equivalent weight of the subject while in the knee bend position at 0 rpm was 4.90 lb. whereas the average equivalent weight of the subject remaining motionless at 0 rpm was 3.66 lbs. See below Figure 25 for the stepping profile and Figure 26 for the bending profile at 0 rpm. In order for the subject to perform the stepping and knee bends, pulling on the stair stepper device with the non-stepping foot was necessary to work against the damping inherent in the stair step machinery.

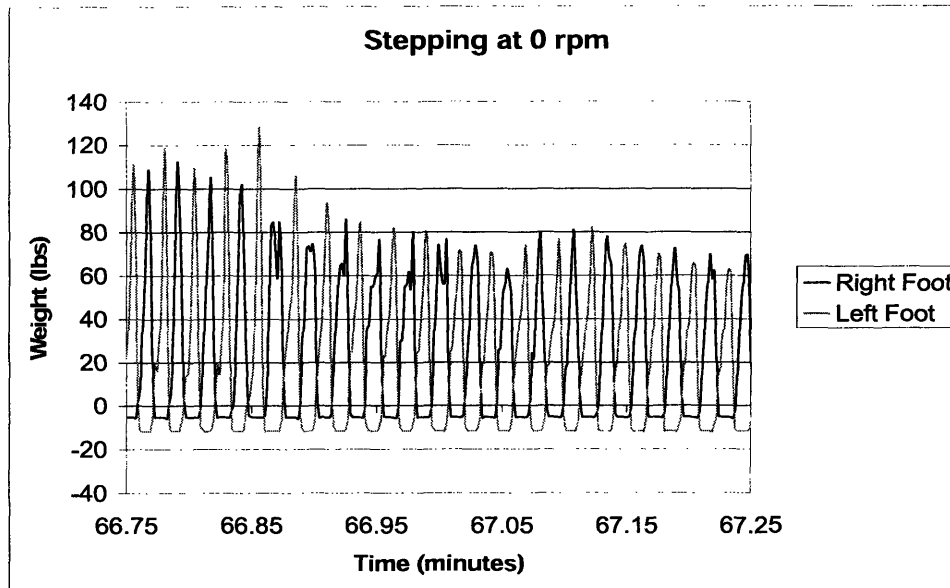


Figure 25: Stepping profile at 0 rpm.

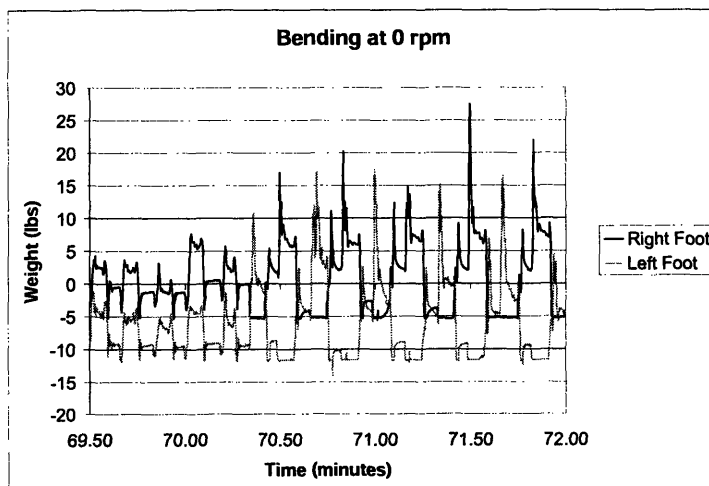


Figure 26: Force profile during knee bends at 0 rpm.



## DISCUSSION

The equivalent weights of the subject were also modeled based on the ideal man proposed by Diamandis. In Model 1 the subject's weight was measured and the height and body segment lengths estimated from the weight. In Model 2 both height and weight were used, but the body segment lengths estimated and in Model 3 height, weight and body segment lengths were recorded for the subject. The first two models come closer to achieving the value output by the electronic scales; however, the third model greatly overestimates the mass of the subject's neck. In addition, none of the models take into account the slider on which the subject rests. Not only does it contribute additional equivalent weight to the torso area, but also the way that the subject rested on the slider may have impacted the measured values. The discrepancy between the modeling situations and the measured values may be due in part to the modeling assumptions, but it is also likely that there is some error in the measurements themselves due to slight hysteresis. See below Table 3 for the subject's equivalent weight modeled in different situations.

**Table 3: Equivalent weights in pounds of subject in different modeling situations.**

Speed	Model 1	Model 2	Model 3	Measured
23 rpm	81.19	77.66	80.58	55.68
30 rpm	138.12	132.10	137.07	104.33

While the subject is resting on the centrifuge, his equivalent weight remains constant at each different speed at which he is spun. The only difference occurs between the speeds. In Figure 18 the forces of the subject exerted outwards on the scales increase monotonically. This was expected from choosing 12.5, 23 and 30 rpm. We had the subject perform a series of knee bends so that we could determine the overall equivalent weight of the subject. As the subject remained still for a period of time while performing the knee bends, we are able to clearly see that the values for the equivalent weight of the two feet sum to a greater value than when the subject is lying still. Equivalent weight increases when performing knee bends as the majority of the body is out at a greater radius than when the subject is lying still.

It is possible from values provided by the scales to gain a more accurate idea of the forces on the subject's feet while exercising on the centrifuge. The maximum forces

exerted by the subject were at 30 rpm while exercising. The minimum values occurred while being still on the centrifuge at 0 rpm, as expected.

The subject stepped significantly harder while performing the stair stepping exercises. He also tended to “bottom out” during some of the exercise procedures. This is evidenced by a sharp spike of force and then flattening of the usually smooth peaks demonstrated during procedures.

The location of the center of mass of the subject also varied slightly depending on the modeling assumptions used. In Model 1 the center of mass of the subject was located at 49% for both the 23 and 30 rpm spins. In Model 2 the center of mass was located at 47% at both speeds. In Model 3 the center of mass was located at 43% for both speeds. In actuality, the center of mass of the subject was located at 30% for 23 rpm and 33% for 30 rpm. The real value was slightly skewed by the addition of equivalent weight near the torso from the slider bed upon which the subject was laying. See below Table 4 for a comparison of the centers of mass.

**Table 4: Center of mass comparison.**

	23 rpm	30 rpm
Model 1	0.43	0.43
Model 2	0.41	0.41
Model 3	0.43	0.43
Real	0.3	0.33

## CONCLUSION

The Contek WCS-20® served well as a prototype for use on board the human centrifuge in the MVL. Two scales were modified so that they could be miniaturized to accommodate their range of motion parallel to one another on the centrifuge. To do this, the wiring was shortened and the original footplates from the Contek WCS-20® were mounted on a smaller aluminum backing. This backing was then mounted on the existing stair stepper device on the centrifuge.

Models were generated in Excel® to predict a subject's equivalent weight at various rpm. The accuracy of the models was varied through inputting more information regarding the subject's body dimensions. These models were compared to the actual values of the subject at 0, 12.5, 23 and 30 rpm. At each of these speeds, the subject was initially still, then performed a series of stair stepping exercises and then squats. The subject's equivalent weight was demonstrated to increase slightly with the squatting exercises as the radius of his body was farther removed from the center of the centrifuge.

Although the models predict, to some extent, the subject's equivalent weight on the centrifuge at the various speeds, they are inaccurate. A better modeling method is needed to be able to calculate a subject's equivalent weight at given speeds on the centrifuge and in different positions. This inaccuracy may be due in part to the modeling assumptions, as humans are not ideally shaped and the effects of the slider bed on the centrifuge were not incorporated into the calculations. The slider itself adds several pounds to the equivalent weight. There is also likely to be some error in the measurements themselves, due to slight hysteresis. In addition to rectifying the modeling assumptions, another prototype of the scales will be created. It will be made significantly smaller and can minimize the range of movement of each of the moveable parts, limiting the potential for error.



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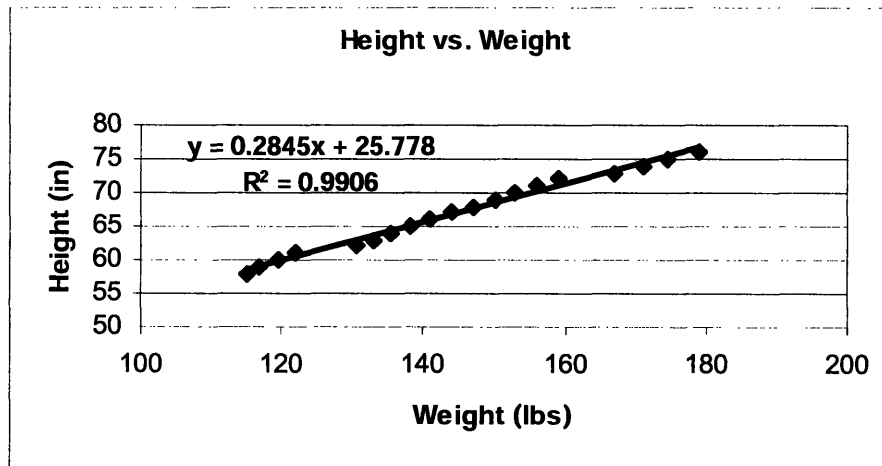
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## APPENDIX A

**Table 5: Body Mass Index Calculations [18].**

Height In Inches	Men Minimum Weight	Men Maximum Weight	Women Minimum Weight	Women Maximum Weight	Average Weight
58	-----	-----	109	121	115
59	-----	-----	111	123	117
60	-----	-----	113	126	119.5
61	-----	-----	115	129	122
62	131	141	118	132	130.5
63	133	143	121	135	133
64	135	145	124	138	135.5
65	137	148	127	141	138.25
66	139	151	130	144	141
67	142	154	133	147	144
68	145	157	136	150	147
69	148	160	139	153	150
70	151	163	142	156	153
71	154	166	145	159	156
72	157	170	148	162	159.25
73	160	174	-----	-----	167
74	164	178	-----	-----	171
75	167	182	-----	-----	174.5
76	171	187	-----	-----	179

**Figure 27: Height vs. Weight graph with recursive equation [17].**







## APPENDIX B

**Table 6: Weight in pounds and associated height in inches.**

	Model 1	Model 2	Model 3
Weight:	174	174	174
Height:	75.28	72.00	72.00

**Table 7: Mass in slugs and associated height in feet.**

	Model 1	Model 2	Model 3
Mass:	5.40	5.40	5.40
Height:	6.27	6.00	6.00
Length:	6.27	6.00	6.00

**Table 8: Mass ratios per body segment.**

Body part	Equivalent weight ratios	Model 1	Model 2	Model 3
		Mass	Mass	Mass
Head	0.05	0.28	0.28	0.28
Thorax	0.37	2.00	2.00	2.00
Arms	0.13	0.69	0.69	0.69
Legs	0.45	2.43	2.43	2.43
Total	1.00	5.40	5.40	5.40

**Table 9: Length ratios and radii per body segment.**

Body part	Length ratios	Model 1		Model 2		Model 3			
		Arm	Radius	Arm	Radius	Actual segment lengths	Length ratios	Arm	Radius
Head	0.06	0.38	0.19	0.36	0.18	13.00	0.18	1.08	0.54
Thorax	0.31	1.95	1.35	1.87	1.29	16.00	0.22	1.33	1.75
Arms	0.36	2.23	1.49	2.14	1.43	31.00	0.43	2.58	2.38
Legs	0.73	4.59	4.62	4.39	4.42	43.00	0.60	3.58	4.21
Total	1.00	6.27	6.16	6.00	5.89	72.00	1.00	6.00	6.50

**Table 10: Calculated m\*r per body segment and forces at 23 and 30 rpm.**

	Model 1		Model 2		Model 3	
	Arm	Radius	Arm	Radius	Arm	Radius
Head m*r	0.11	0.05	0.10	0.05	0.30	0.15
Thorax m*r	3.90	2.70	3.73	2.59	2.67	3.50
Arms m*r	1.53	1.02	1.47	0.98	1.77	1.63
Legs m*r	11.15	11.24	10.67	10.75	8.71	10.23
Total m*r	16.69	13.99	15.96	13.38	13.46	13.88
23 rpm real	96.86	81.19	92.64	77.66	78.09	80.58
30 rpm real	164.77	138.12	157.59	132.10	132.85	137.07

**Table 11: Measured forces in pounds by foot at 23 and 30 rpm.**

Speed	Left foot	Right foot	Total
23 rpm	31.13743	24.53947	55.6769
30 rpm	54.79116	49.5355	104.327

## APPENDIX C

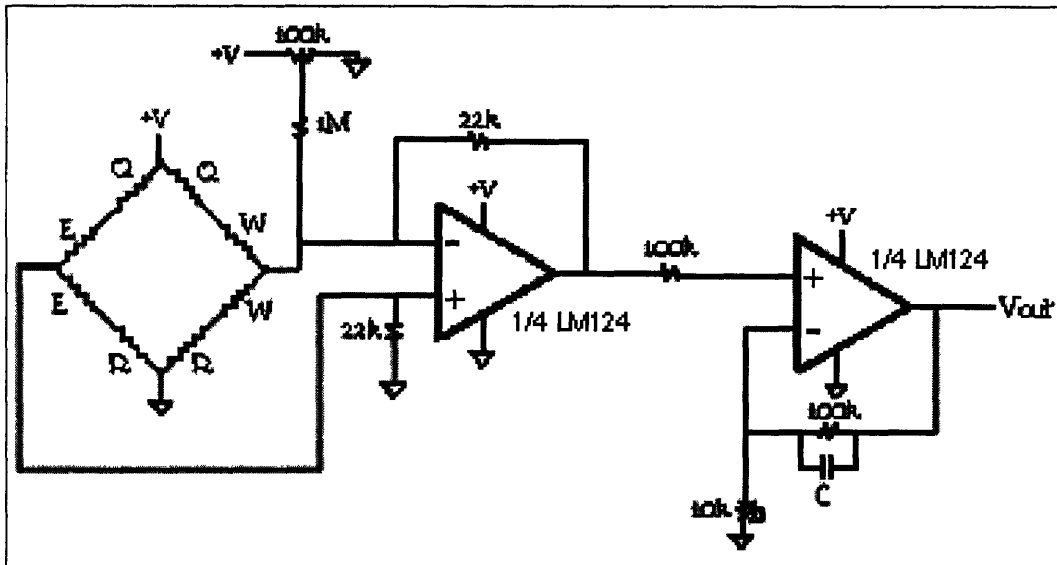


Figure 28: Amplifier circuit used.

The circuit uses two op amps to amplify the signal. The feedback loops with the resistors going across the op amps from the negative side to the out side are used to modulate the gain.

The signal initially coming out of the eight resistors needed to be output at a level which could be detected reasonably easily and yet still have enough specificity to detect small changes in the force. The first op amp amplifies the signal through changing the resistor. Initially, we intended to use a 100k resistor, but found that we needed a 22k resistor to get an output voltage in the range that we wanted. The second op amp allows us to have more sensitivity for minute adjustments so that we could calibrate the system. Other changes made to the circuit included adding a variable resistor before input 1- and adding a capacitor between input 2- and output 2.

Each footplate of the scale has two resistors in series located within it. The four wires coming out of the circuit leading to +V, ground and the + and - ends of the first op amp are red. The wires connecting E to Q and R to W are white. The wires connecting

Q to W and E to R are blue. Two of the eight resistors are located inside each foot plate. They are oriented perpendicular to one another to measure strain.

## APPENDIX D

**Table 12: Recorded times of events during experiment.**

Data Time	Actual Time	Data Label
10	0-0.17	0 still
230	1.17-3.83	12.5 still
360	4.83-6.00	23 still
495	7-8.25	30 still
830	9.25-13.83	30 rpm exercise
1025	14.83-17.08	30 rpm squats
1675	19.82-27.92	23 rpm exercise
1820	28.97-30.33	23 rpm squats
2955	32.80-49.25	12.5 rpm exercise
3085	50.25-51.42	12.5 rpm squats
4040	54.08-67.33	0 rpm exercise
4180	68.33-69.67	0 rpm squats

Additional time spent between rest periods, stair stepping and squats allowed the centrifuge to be spun up and down to the various speeds.



# **APPENDIX E**

## **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., Jessica Edmonds and Kevin R. Duda, graduate students 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.

- **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**

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

When you arrive 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. Data collection devices could include heart rate sensors (the over-the-counter chest strap, commonly used by athletes), optical motion analysis cameras, surface electromyography (EMG) electrodes, and force sensors on the footplates. After your briefing, the experimenter will record your answers to basic questions about your health, and take your height, weight, blood pressure, and heart rate.

Before lying on the centrifuge, you will be asked to perform some type of exercise upright in the lab, which may be knee bends, use of a stair-stepper device, or other common exercise. Data will be collected during this time, and you will exercise for approximately ten minutes.

During the experiment you will lie on the centrifuge in the supine position. You will be asked to either place your head on a pillow or into a cushioned helmet at the center of the centrifuge that helps you not to turn your head. After lying down, the experimenter will collect data while the centrifuge is stationary, and allow you to rest for approximately ten minutes. After this rest period, you may perform exercise while the centrifuge is stationary. Data will be collected, and you will exercise in the supine position for approximately ten minutes.

The experimenter will ask you if you are ready before starting rotation. Your rotation on the AG centrifuge will not exceed the following parameters:

- Acceleration no greater than 1 revolution per minute, per second
- G-level at your heart no greater than 1g, AND PROPORTIONALLY GREATER G'S AT THE FEET (a "g-level" is defined as the acceleration or force that you would experience normally standing on earth)
- Time of rotation not exceeding 1 hour

Exercising may be in the dark and/or in the light. Your level of exercise (speed at which you pedal, perform knee bends, etc.) will be at your discretion. During this time 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.). 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, the centrifuge will be stopped, and the experimenter may collect some additional data.



As a participant in experimental trials, you tentatively agree to return for additional trials (at most 5) requested by the experimenter. You may or may not be assigned to a study group that performs similar tasks. Other than the time required for rotation (which is estimated to last approximately 45 minutes), the time commitment is 20 minutes for the first briefing, 10 minutes for the upright exercise condition, and 10-60 minutes for other procedures before and after rotation. The total time for participation in one day will be approximately 2 hours.

- **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.

The procedure may involve risks that are currently unforeseeable.

- **ANTICIPATED BENEFITS TO SUBJECTS**

You will receive no benefits from this research.

- **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 \$10/hr for their participation. 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

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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

\_\_\_\_\_

