Physiological and Comfort Assessment of the Gravity Loading Countermeasure Skinsuit During Exercise

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Abstract— **The microgravity environment causes physiological deconditioning in astronauts due primarily to the absence of skeletal loading. The Gravity Loading Countermeasure Skinsuit (GLCS) is a proposed countermeasure for the musculoskeletal system. The suit provides the wearer with a static load regime replicating Earth's gravity by increasing the vertical load from the shoulders to the feet. A first prototype of the GLCS was developed, and a pilot study conducted during a parabolic flight campaign resulted in reasonable suit comfort and negligible impact of mobility during basic, low-metabolic movement. However, in order for the GLCS to serve as a countermeasure in future missions, it must also be unobtrusive and comfortable during active periods of intra-vehicular activity such as exercise. Hence, the purpose of this pilot study was to gain a better understanding of the physiological and comfort responses to wearing the GLCS during simulated exercise in microgravity, using a cyclometer in the supine position (6 degrees head down tilt) with the downstroke of the cycle perpendicular to direction of gravitational acceleration. Two subjects followed an exercise cyclometer protocol with and without the skinsuit. Heart rate and respiration chest pressure rate were measured in order to assess any physiological differences while exercising in the GLCS. In addition, force plates were mounted on the pedals to record the force in the Gz axis and validate previously measured loads imposed on the feet by the suit. Qualitative feedback regarding comfort and mobility was also collected after the trials. Preliminary results from the physiological measurements showed that the suit resulted in no significant difference from the unsuited condition in any of the parameters. Comfort results showed that subjects would be able to wear the suit for up to 16 hours with only minor discomfort. These preliminary results indicate that the GLCS may be wearable during exercise, thereby reinforcing the initial design philosophy of that suit that it could be worn for extended periods inside the spacecraft. Further, the combination of static skeletal loading provided by the suit with the aerobic exercise of cycling may serve as a combined future countermeasure to spaceflight deconditioning.**

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1. INTRODUCTION

Astronauts suffer strong physiological deconditioning in space, due primarily to the microgravity conditions to which they are exposed during spaceflight. Bone loss, muscle atrophy, blood circulation regulation loss, and decreased aerobic capacity are some of the effects of prolonged weightlessness [1]–[7].

Bone loss is one of the most important forms of physiological deconditioning that occurs during spaceflight. Bone loss in space occurs primarily because of the absence of skeletal loading in microgravity [1], [8], [9]. Other factors, such as low light levels, high concentration of CO_2, dietary deficiencies (calcium and vitamin D), and genetic factors also affect the skeleton properties. In addition, unloaded skeletal conditions lead to a significant loss of calcium in the bones and a substantial increase in the risk of kidney stone formation [1], [8].

Bone is a living tissue and is under constant remodeling throughout its lifetime. Frost's mechanostat theory suggests that the response of bone to mechanical loads is controlled by a "mechanostat" that adjusts and adapts bone tissue according to the needed mechanical function [10]. Depending on the load applied, bone can be resorbed (i.e. loss of bone mass and therefore strength), remodeled (bone replacement), or modeled (i.e. bone gain). During the remodeling process old bone is replaced by new bone, helping to avoid the accumulation of microdamage [11]. Bone remodeling is highly dependent on the mechanical loading applied on the skeleton [1], [8], [11]–[14]. Two types of mechanical loading can be distinguished: static loading and dynamic loading. An obvious example of static loading is the gravity force. People on Earth are continuously subjected to the gravity force, and this gravitational acceleration has an important role in skeletal remodeling. On the other hand, dynamic loading may include short periods of high-impact peak loads (such as ground reaction forces while running or jumping) or frequent low-level loading (such as low frequency vibration). Lastly, muscle contraction also plays an important role in skeletal loading [8], [13]. The muscle forces developed to move the limbs in 1G also contribute to bone remodeling. In weightless conditions, skeletal mechanical loading is highly reduced because of the absence of gravity and ground reaction forces, and also the significant reduction of muscle forces generated

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to move in space, especially in the lower limbs [1], [8]. The reduced loading therefore leads to an increase in rate of bone resorption and a decrease in rate of bone remodeling and modeling.

In this gravitationally unloaded environment, astronauts also experience muscle deconditioning during spaceflight [1], [15], [16]. Muscles experience an imbalance between two processes - muscle protein synthesis and muscle protein degradation - leading to losses of muscle mass and strength. Eventually, muscle protein synthesis and muscle protein degradation will stabilize at a reduced equilibrium point involving lower muscle mass. Causes of muscle deconditioning include the lack of activity, under-nutrition, stress, oxidative stress (refers to the balance between oxidants/antioxidants), and hormonal influences [1].

Penguin suit— A current in-flight countermeasure used for the Russian cosmonauts is the Zvezda Penguin suit. This whole-body suit includes elastic bungee cords to partially simulate gravitational loading on the human body (see Figure 1). Two sets of elastic cords are attached to a leather belt and they provide upper body loading (cords from the shoulder to the belt) and lower body loading (cords from the belt to the feet). The suit creates compression along the body's longitudinal axis (z-axis), providing constant static loads and resistance to movement and thus, stressing and stimulating the musculoskeletal system [8], [17].

The "Penguin" suit can produce a static axial loading up to 70% of the bodyweight during treadmill training. The upper body can produce axial and static loading up to 40 kg [18]. This load can be increased by shortening the leg cords. The calf muscles are also loaded by adjusting the cords on the boots [8].

Despite all the potential musculoskeletal benefits provided by the use of the "Penguin" suit, cosmonauts have found the suit highly uncomfortable. Thus, they have individually loosened, or even cut, the elastic cords to improve their comfort. In addition, the suit has been used in conjunction with other countermeasures, making a proper evaluation and quantification of its effectiveness very difficult [8].

Figure 1: The "Penguin" suit (Left: Kozlovskaya 2004; Right: drawing by Philippe Tauzin, Clement 2005)

The Gravity Loading Countermeasure Skinsuit—The Gravity Loading Countermeasure Skinsuit (GLCS) also provides the wearer with a continuous static loading regime replicating that of gravity on Earth. In contrast to the "Penguin' suit, the GLCS gradually increases the vertical load from the shoulders to the feet (z axis), mimicking the loads imposed on the different parts of the body under gravitational conditions. The GLCS contains bands to produce several vertical stages. Each of these stages produces a slightly different vertical loading that increases from the torso to the feet. The GLCS also provides a low circumferential tension to avoid suit slippage in the body's Gz axis. The GLCS could be combined with current exercise countermeasures devices to improve the dynamic loading generated while exercising, and this combination may reduce physiological deconditioning during long duration spaceflight [8], [9]. A conceptual design of the GLCS is shown in Figure 2.

A first prototype of the GLCS was developed and a pilot study conducted under microgravity conditions during a parabolic flight campaign. Some practical aspects of the skinsuit were studied, such as mobility and comfort with basic movements (not exercising). Results showed a reasonable suit comfort and negligible impact of mobility [8]. In order for the GLCS to serve as a countermeasure in future missions, it must not only be effective and comfortable during passive activity, but also during active periods of intra-vehicular activity such as exercise , which is the principal countermeasure used in space and an extremely important part of astronauts' daily activities [8], [9].

Exercise in the ISS— The exercise devices onboard the ISS include the Advanced Resistive Exercise Device (ARED), the Cycle Ergometer with Vibration Isolation System (CEVIS), the VELO ergometer, and the T2 treadmill (also known as the Combined Operational Load-Bearing External Resistance Treadmill, or COLBERT), which replaced the Treadmill with Vibration Isolation System (TVIS). Astronauts spend 2 – 2.5 hours per day (including time for set-up and hygiene), 6 days per week on the exercise equipment, rotating between the devices each day as prescribed by individual routines developed based on astronaut preference.

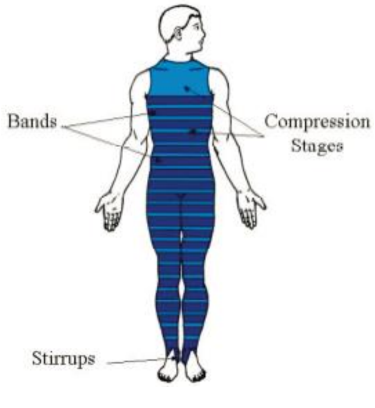

Figure 2: Conceptual design of the GLCS (Waldie 2010)

These devices provide a large spectrum of exercise possibilities, including both aerobic and resistive exercise [19]–[22]. In particular, the two ergometers onboard provide the capability of doing aerobic exercise at different resistances and positions. The Russian VELO ergometer is used in the recumbent position and it is able to provide resistances between 50-250 W at 40-120 rpm. It can also be configured to be used as a cable resistive device for upper body work. On the other hand, the US CEVIS ergometer is used is a more traditional upright position and it is able to provide resistances between 25-350 W at 50-120rpm. The CEVIS can be configured to be used as a hand crank [22].

Exercise with the Gravity Loading Countermeasure Skinsuit—Previous studies at King's College in London have investigated the combination of the GLCS with exercise. In particular, the authors performed aerobic tests consisting of two different twenty minute cycles (with GLCS and non-GLCS) using both upright and recumbent ergometers (see Figure 3). Eight subjects participated in the study with custom made GLCS suits, and cycle workloads were individually adjusted to 75% of predicted VO_2max. Authors did not find significant differences in heart rate, lactate, core temperature, oxygen consumption (VO_2), or carbon dioxide production (VCO_2) between the GLCS and the non-GLCS, or between ergometer orientations. Minute ventilation (V_E, in l/min) was the only parameter significantly higher in the GLCS condition. In addition, subjective reports showed that comfort and body control were significantly worsened when wearing the GLCS. Despite these differences, results suggest that ergometer exercise while wearing the GLCS remains achievable [23].

Figure 3: Upright [23] (left) and recumbent [24] (right) ergometer used during the experiments at King's College

Objectives of Our Work—The purpose of this study is to expand the work done by King's College in order to gain a better understanding of the physiological responses to wearing the GLCS during exercise. In contrast to previous work, participants exercise using a cyclometer in the supine position (6 degrees head down tilt), with the direction of the cycle downstroke perpendicular to the gravity vector, in order to better simulate microgravity conditions. In addition, subjective measurements of comfort and mobility (body control) during exercise are also included in our study.

Hypothesis/Specific Aims—In the current pilot study, we hypothesize that the GLCS is wearable during exercise activities in simulated microgravity at 6° head-down tilt, making this combination (GLCS and exercise) a potentially better countermeasure against astronaut physiological deconditioning during long duration spaceflight. In addition, we aim to make recommendations for future design iterations of the suit, as well as future research.

2. METHODS

Subjects—For this preliminary study, two female subjects participated in the experiment. Table 1 shows the details of the selected subjects. Before the trials, subjects completed a questionnaire to assess participant eligibility, based on general health requirements and previous injuries. The Committee On the Use of Humans as Experimental Subjects (COUHES) at MIT approved this study, and all subjects gave informed written consent prior to participating.

Table 1: Selected subjects

	Subject 1	**Subject 2**
Age	28	22
Gender	Female	Female
Height (m)	1.68	1.73
Mass (kg)	61.2	65.8

Exercise protocol and measurements—Each subject participated in two different sessions (with and without the GLCS suit) consisting of a 15-minute exercise cyclometer protocol. Heart rate and respiration rate (both from Vernier Software and Technology, LLC) were measured in order to assess any physiological differences while exercising in the GLCS. In addition, force plates (Vernier Software and Technology, LLC) were mounted on the pedals to record the force in the body's Gz axis that the subjects exerted while pedaling. Finally, the rate of cycling in revolutions per minute (RPM) was also measured. Respiration rate, foot forces, and cycling rate data were tested for homoscedasticity using the Levene's test, and for normality using the Kolmogorov-Smirnov test. In all cases, significance was taken at the $\alpha = 0.05$ level.

The exercises were completed on a "0-gravity exerciser" constructed by the team. The device positioned subjects at a 6^o head-down tilt and eliminated the gravity vector in the 'downward' stroke of the cycle. The 0-G exerciser accommodates subjects within the anthropometric range of the NASA astronaut population, and includes an adjustable-length baseplate to accommodate interchangeable exercise devices [25], [26]. For this study, the Lode Angio cycle ergometer was used (Lode BV, Groningen, Netherlands). This exercise device is also being used in other facilities doing space exercise research, such as the Institute for Biomedical Problems (IBMP), the German Aerospace Center (DLR), and NASA Ames [27]. Figure 4 shows the design of the 0-G exerciser.

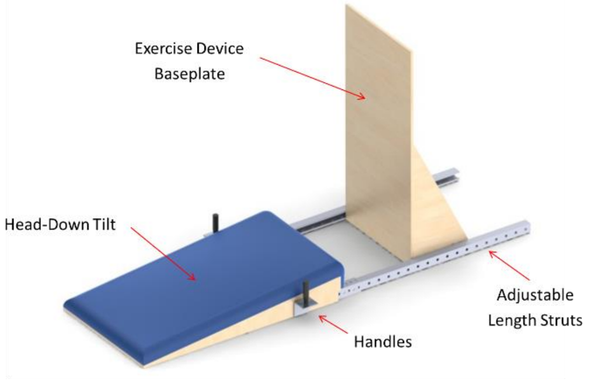

Figure 4: 0-G exerciser

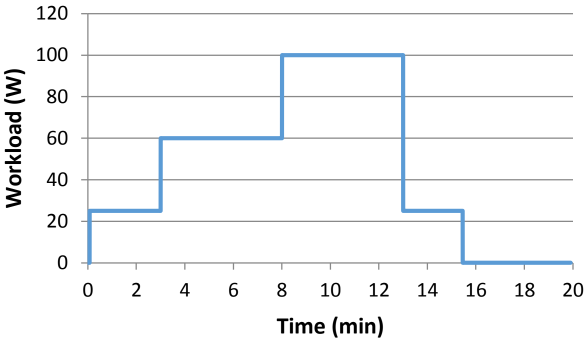

Figure 5: Exercise protocol during the pilot study

Each 15-minute exercise session consisted of four phases. In the first one, or "warm up" phase, subjects cycled at low workload (25 W) for 3 minutes. During the second phase, subjects cycled at moderate workload (60 W) for 5 minutes. During the third phase, subjects cycled at high workload (100 W) for 5 minutes. Lastly, subjects "cooled down" at low workload (25 W) for 2 minutes. Figure 5 shows the exercise protocol during each 15-minute exercise session.

The Lode Angio cycle ergometer was configured in a "hyperbolic" mode, meaning that during the exercise protocols, the workload was kept constant, independent of the RPM. In this mode, if a subject started pedaling at lower RPM, the cycle torque (or pedaling resistance) was automatically increased so the workload seen by the subject was kept constant. Thus, confounding factors related to the subject pedaling speed were avoided.

Additional qualitative feedback from subjects was collected via questionnaires administered after the trials to assess suit comfort. Subjects were asked to rank their comfort of various body parts on a modified Corlett and Bishop discomfort scale and modified Cooper-Harper scale from 1 (more comfort) to 10 (less comfort), where each number in the scale was accompanied by a sentence description (see Table 2). The descriptions allowed a more accurate assessment of comfort/discomfort with the GLCS.

Table 2: Modified Corlett and Bishop Discomfort and Cooper-Harper body control scale [8]

Rating	Discomfort	Body control (mobility)
1	Nude comfort	Unrestricted
2	Pajamas, casual clothes	Negligible deficiencies
3	Formal attire	Minimal compensation required
4	Minor discomfort if worn all day (16 h)	Minor but annoying deficiencies
5	Too uncomfortable to wear all day	Moderately objectionable deficiencies
6	Too uncomfortable for 8 h	Tolerable deficiencies
7	Too uncomfortable for 4 h	Maximum tolerable compensation required
8	Too uncomfortable for 2 h	Considerable compensation required
9	Too uncomfortable for 1 h	Intense compensation required
10	Too uncomfortable for 10 min	Body lost control

Subjects completed their trials at the same time on two separate days. Figure 6 shows one subject during a suited trial. The temperature and humidity in the room were measured before each trial to ensure that subjects were exercising in a comfortable and consistent environment. During the four trials room temperature ranged from 20-22°C, and the relative humidity ranged from 21-35%.

3. RESULTS

Physiological Results—All data were collected using two software suites: Logger Lite (heart rate and respiration rate, and foot forces) and the Lode Ergometry Manager (cycle workload and cadence in revolutions per minute (RPM)).

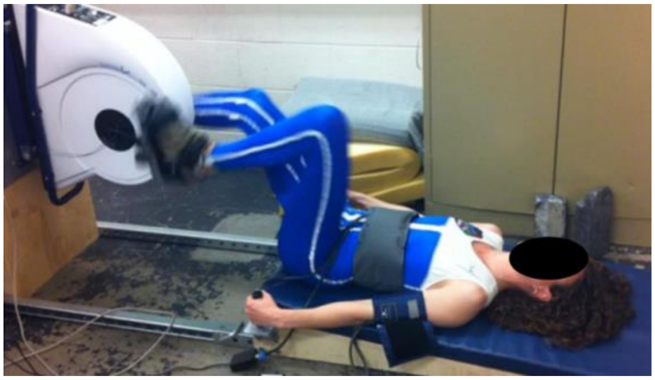

Figure 6: Subject wearing GLCS during a trial

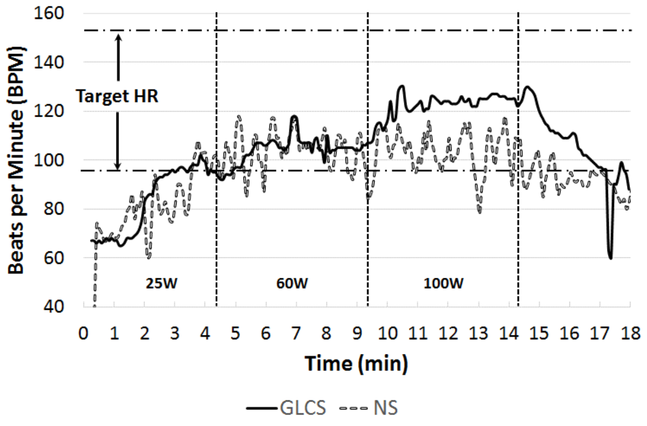

Figure 7: Heart rate measured from subject 1 during the exercise protocol, suited (GLCS) and non-suited (NS).

An additional sensor error occurred with the heart rate monitor belt, resulting in a loss of data for one of the subjects. Figure 7 shows the data that was collected successfully for subject 1. This figure also indicates the three workload phases of the trials as well as the upper and lower bounds of the subject's target heart rate. Target heart rate is defined as between 0.5*(220-$\text{Age}_{\text{subject}}$) and 0.8*(220-$\text{Age}_{\text{subject}}$), measured in beats per minute (BPM).

Respiration rate was analyzed by converting pressure data from the respiration belt to the frequency domain using the Fast Fourier Transform (FFT). The frequency analysis was done separately for each of the three phases of exercise. An example of the frequency plots for one trial (Subject 1, non-suited) is shown in Figure 8 as an example of the type of analysis done.

The respiration belt had to be manually inflated for each trial which resulted in slight variations in initial pressures. As a result, magnitudes of the respiration frequencies could only be compared within trials, and not between them. The amplitude of respiration was therefore baselined to the initial phase (workload = 25 W) for each set of frequency analyses, with the peak amplitude at 25 W being equal to 1. Thus, comparison could be made between the three phases with different workloads (25 W, 60 W, 100 W). As an example, in Figure 8 the amplitudes of the peak frequencies during the 60 W and 100 W phases of the trial indicate that they were approximately 20% higher than the peak amplitude at the 25 W workload. An increase in peak amplitude above the baseline was seen during all 60W and 100 W phases across trials, with one exception (subject 1 – GLCS) in which the 100 W amplitude was 0.6 with respect to the reference amplitude at 25 W.

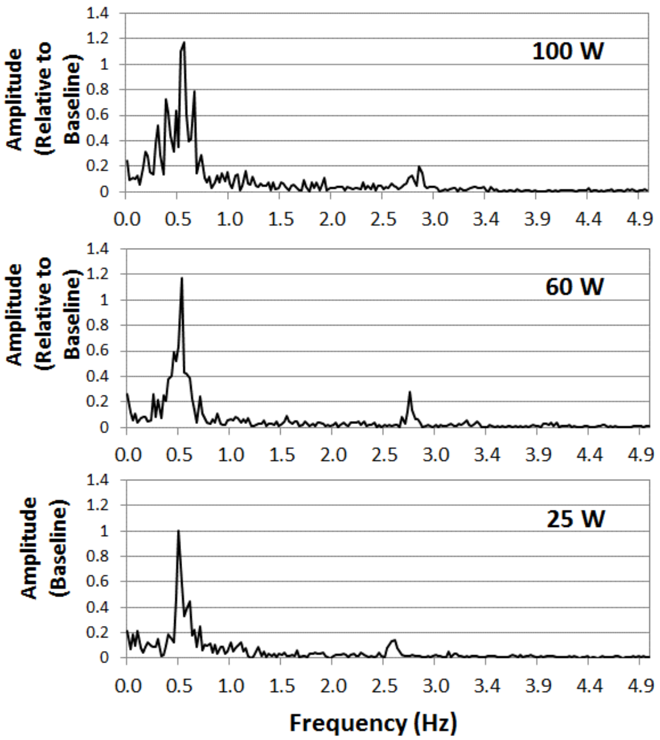

Figure 8: Example of respiration rate frequency data from subject 1 (non-suited) during the exercise protocol.

The peak frequency for each phase of each trial was identified and they are summarized in Table 3. A two-way, repeated measures ANOVA demonstrated that there was no significant effect of the suited condition (p-value = 0.465), no significant effect of workload (p-value = 0.290) and no interaction effect between the two factors (p-value = 0.583) on respiration rate.

Foot forces were analyzed by separating the data into the three phases of interest for each trial. The peaks were then analyzed by two-pass filtering the local maxima. An example of the foot force data analysis can be seen in Figure 9. Foot forces were assumed to be equal between the two feet, thus only the left foot was analyzed for each trial.

Table 3: Respiration rate peak frequencies (Hz) for subject 1 and 2, in each one of the two conditions: non-suited (NS) and suited (GLCS).

	Subject 1		**Subject 2**	
	NS	**GLCS**	**NS**	**GLCS**
25 W	0.54	0.49	0.37	0.51
60 W	0.44	0.46	0.44	0.54
100 W	0.56	0.49	0.54	0.56

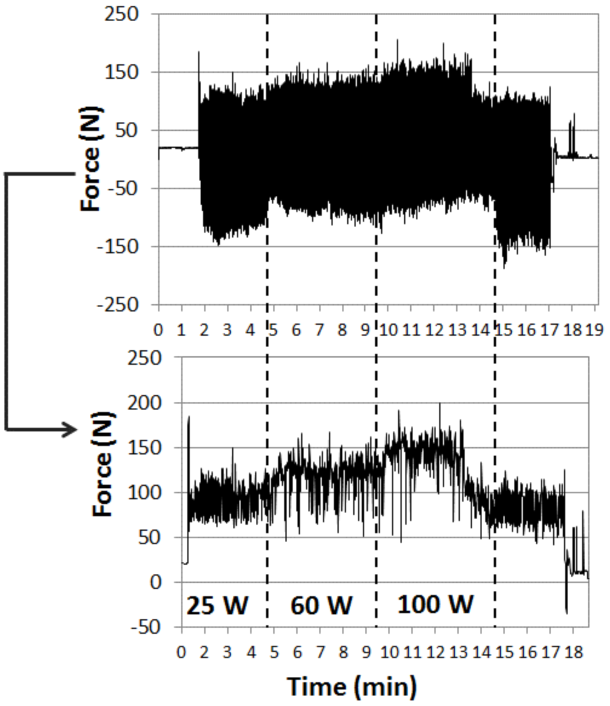

Figure 9: Example of foot force data (top) and peak force after filtering (bottom) collected from subject 1 (GLCS condition) during the exercise protocol.

The peak foot forces were then averaged for each phase within trials. Table 4 summarizes the results. A two-way repeated measure ANOVA showed that there was no significant effect of the suited condition (p-value = 0.557). However, there was a significant effect of workload (p-value = 0.002). There was no interaction effects (p-value = 0.212).

Cycling rate data were also analyzed by evaluating the three phases of interest in each trial separately. An example of the cycling rate (subject 1 – GLCS condition) is shown in Figure 10. The cycling rate was averaged during each phase of each trial and summarized in Table 5. Results of a two-way repeated measures ANOVA demonstrated that the cycling rate was not significantly affected by either the suited condition (p-value = 0.284) or the workload (p-value = 0.755). In addition, the interaction effects were not significant (p-value = 0.856).

Table 4: Average peak foot forces (N)

	Subject 1		**Subject 2**	
	NS	**GLCS**	**NS**	**GLCS**
25 W	84.27	96.87	63.47	89.29
60 W	123.8	120.7	97.36	109.4
100 W	144.5	127.7	134.0	127.0

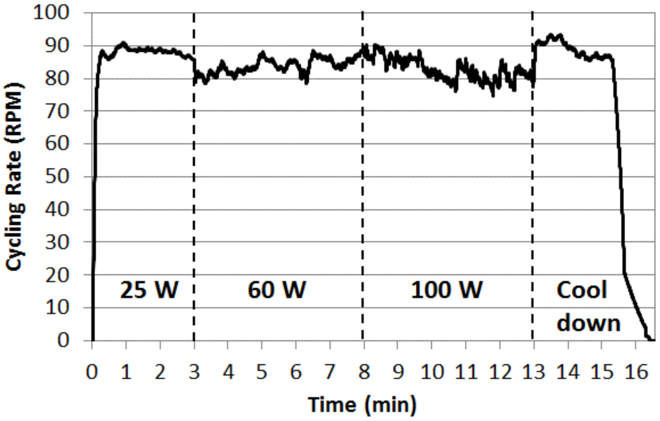

Figure 10: Example of cycling rate data-collected from subject 1 (GLCS condition) during the exercise protocol.

Comfort Results—Each subject completed two exit surveys, one after each test session, including ratings on discomfort and body control (mobility) on different parts of the body. Three conditions were rated: cycling only (with no suit), suited only, and suited while cycling. In addition, subjects also had the opportunity to report any other subjective data relevant to the exercise session.

Responses for comfort level are presented in Figure 11. Results indicate that comfort levels are very different between the subjects. It is important to note that both subjects used the same suit, which was customized for subject 1. Due to the differential loading in the suit, one might expect an increase in discomfort around the subject's feet while wearing the suit, as seen in the results from subject 1.

Two additional observations can be made comparing comfort ratings between conditions. First, there was a slight increase in discomfort when cycling with the suit compared to just cycling, particularly for subject 2. Subject 1 showed an increase in discomfort during the "cycling alone" condition, probably due to the fact that this was the first time the subject used this particular ergometer. In addition, subjects responded that cycling with the suit and just wearing the suit led to similar levels of discomfort. For subject 1, the levels of discomfort are very similar between these two conditions (suit and suit + cycling) throughout most of the body while Subject 2 had roughly the same variance of discomfort along the body, but cycling in the suit was more comfortable than just wearing the suit. Possible reasons and recommendations will be discussed in the next section.

Table 5: Average cycling rate (RPM)

	Subject 1		**Subject 2**	
	NS	**GLCS**	**NS**	**GLCS**
25 W	81.76	76.38	57.66	86.2
60 W	88.23	83.86	65.85	80.54
100 W	74.72	82.48	82.42	82.71

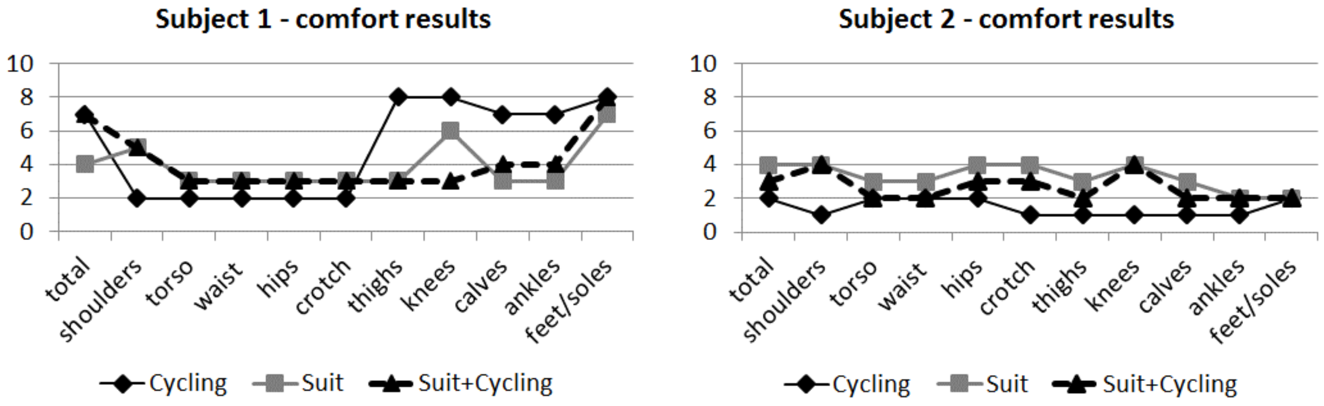

Figure 11: Comfort results from subject 1, shown on the left, and subject 2, shown on the right. The comfort scale ranged from 1 (nude comfortable) to 10 (too uncomfortable for 10 min).

Additionally, both subjects reported that their quadriceps were sore after each cycling session, and this occurred whether they were wearing the suit or not. They both mentioned that the shoulder yoke of the suit was uncomfortable. Subject 2 also mentioned discomfort in the hip/crotch area and upper leg; the suit's loading felt strange but was less when biking. Subject 2 hypothesized that it was because her hips were bent, and because the suit wasn't customized for her. Subject 1 also mentioned that the foot stirrups were uncomfortable, and during the suit + cycling session, the balls of their feet fell asleep. Lastly, both subjects indicated that the exercise regimen was somewhat strenuous (level 3 out of 1-5). They both stated that the difficulty was due to the resistance of the ergometer, not the length of the trial.

4. DISCUSSION

Physiology—Despite the fact that heart rate data was limited to one subject, the observed trends raise interesting questions for further study. Subject 1 was within their target heart rate range during nearly the entire 60 W and 100 W phases of the trial while in the GLCS, but not while unsuited. Further studies are needed to show whether this trend was specific to the subject, was the result of sensor error, or is in fact significant.

The results of the respiration rate analysis showed that the GLCS had no significant effect on the frequency of respiration rate. A trend of respiration magnitude to increase as workload increased was seen across all trials, regardless of the suited condition. It is therefore likely that the elevated oxygen demand that resulted from increased workload was met by deeper breathing as opposed to faster breathing. However because of limitations which prevent frequency magnitude comparisons between trials this must be tested further.

Analysis of peak foot forces showed that the GLCS had no effect on this parameter. However, there was a significant effect from workload. The fact that there was no significant effect from either the suit or the workload in cycling rate implies that subjects were meeting the higher workload demand by pedaling harder, not faster. These results were similar for both suited and unsuited subjects.

Results from the foot forces also validated the design of the 0-G exerciser in simulating the microgravity environment with respect to foot forces. Recorded foot forces on the CEVIS ergometer from astronauts exercising in the ISS ranged from 7.0% to 19.0% of bodyweight, with workloads from 75 to 210 W [28]. For the subjects in our study, average peak forces ranged from 13.1%-22.4% of body weight for Subject 1 and 9.98%-20.0% of bodyweight for Subject 2. Thus, the forces measured on the 0-G exerciser in simulated microgravity were within the same range as those measured in actual microgravity.

In conclusion, trends and results revealed from the physiological data gathered during this pilot study suggest that the GLCS do not have a significant effect on any of the measured parameters.

Comfort—Using a qualitative scale to measure the subjects' discomfort led to highly subjective results. This is not surprising, as tolerance of discomfort level, intensity, position, and type (pressure, rubbing, pinching, heat, etc.) may be different between people. Both subjects indicated that overall, the suit would cause minor discomfort if worn all day, defined as 16 hrs. This corresponds to level 4 on the Corlett and Bishop Discomfort scale. However, the 'troublesome' areas were different between the two subjects. It should be stated again that some of the discomfort experienced by subject 2 likely arose from the fact that the subject was wearing a suit that was not tailored to them. While subjects 1 and 2 are similar in height, there still exist noticeable differences in other physical features such as torso and leg lengths, leg circumference, etc. Because these suits are skintight compression garments, even slight variations in body type can cause discomfort. Subject 2 did note that they felt too tall for the suit. They also noted that the ‘gravity’ pull of the suit seemed to pull their legs back to the straight position. As the suit is ‘anchored’ by the subject’s shoulders and feet, it is unsurprising that both found the shoulder yoke to be a component of discomfort, as well as the feet for Subject 1.

As previously stated, it is premature to claim definitive results on comfort level of the suits while exercising. However, the results are promising and do suggest that further trials with more subjects should be conducted.

5. CONCLUSION

Summary—A preliminary physiological and subjective comfort assessment was done on the GLCS while exercising in simulated microgravity. The physiological data gathered showed that the GLCS had no significant effect on any of the measured parameters. However, due to data and subject number limitations, these results should be interpreted with caution and further studies should be conducted. The suit resulted in no significant difference from the unsuited condition in any of the physiological parameters measured. Comfort results showed that subjects would be able to wear the suit for up to 16 hours with only minor discomfort. Results of this initial study indicate that the GLCS may be wearable during exercise, thereby reinforcing the initial design philosophy that the suit could be worn for extended periods inside the spacecraft. Further, the combination of static skeletal loading provided by the suit with the aerobic exercise of cycling may serve as a combined future countermeasure to spaceflight deconditioning. Furthermore, the use of the GLCS combined with the benefits of artificial gravity and ergometer exercise [29]–[35] could be a more complete integrated countermeasure against human deconditioning in space.

Limitations—The primary limitation of the current study was the number of subjects, which itself was limited by the availability of actual GLCS. Given that each suit is supposed to be tailored specifically to each individual, one subject was wearing a suit that was not tailored specifically for her, which could have affected the results, particularly as they relate to comfort. Errors and drop outs in the blood pressure and heart rate sensors also limited the opportunity for a thorough analysis of those parameters.

Future Work—Future work should begin with the fabrication of additional suits in order to increase the number of subjects able to participate, in both males and females. New and improved versions of the GLCS have already been made, both at MIT and King’s College, and they could be used for future investigations. Updated blood pressure and heart rate sensors are also needed for more reliable data collection. Future studies might also investigate different types of exercise regimens, potentially ones that last longer at lower workloads. In addition, a flight version of the GLCS is planned to be assessed during normal daily activities in the International Space Station (ISS) in late 2015.

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