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A gravity loading countermeasure skinsuit

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ABSTRACT

Despite the use of several countermeasures, significant physiological deconditioning still occurs during long duration spaceflight. Bone loss – primarily due to the absence of loading in microgravity – is perhaps the greatest challenge to resolve. This paper describes a conceptual Gravity Loading Countermeasure Skinsuit (GLCS) that induces loading on the body to mimic standing and – when integrated with other countermeasures – exercising on Earth. Comfort, mobility and other operational issues were explored during a pilot study carried out in parabolic flight for prototype suits worn by three subjects. Compared to the 1- or 2-stage Russian Pingvin Suits, the elastic mesh of the GLCS can create a loading regime that gradually increases in hundreds of stages from the shoulders to the feet, thereby reproducing the weight-bearing regime normally imparted by gravity with much higher resolution. Modelling shows that the skinsuit requires less than 10 mmHg (1.3 kPa) of compression for three subjects of varied gender, height and mass. Negligible mobility restriction and excellent comfort properties were found during the parabolic flights, which suggests that crewmembers should be able to work normally, exercise or sleep while wearing the suit. The suit may also serve as a practical 1 g harness for exercise countermeasures and vibration applications to improve dynamic loading.

1. Introduction

For over a century, it has been widely accepted that bone responds to the mechanical loading placed upon it [1,2]. The inherent unloading during spaceflight therefore poses a high risk to skeletal health [3–6]. In particular, astronauts lack the normal static loading due to standing in 1 g, but also the dynamic loads caused by impact and muscle activation during movement. Despite current spaceflight countermeasures, the mineral density loss from weight bearing bones in microgravity is approximately 1–2% per month, with non-weight bearing areas affected more in the long-term [7–11]. Bone loss may be the most important limiting factor for long-term spaceflight, due to the risk of fracture [7,8,12]. This fracture risk is expected during situations of high skeletal strain, such as after returning to Earth (1 g), during activities on Mars or the Moon, during hypergravity exposures of 1.5–5 g at liftoff and aerobraking, and even during strenuous activities in weightlessness, such as extravehicular activity (EVA) [8,13]. The lack of normal loading during spaceflight also causes astronauts to suffer from painful spine elongation of up to 70 mm, with significant back pain reported by approximately 50% of crewmembers [14,15]. Further, this elongation complicates the precise fitment of extravehicular activity (EVA) spacesuits. Skeletal atrophy also increases the likelihood of kidney stones.

There are currently no effective methods to prevent skeletal deconditioning during long duration exposure to microgravity, although new resistive exercise equipment is intended to put greater loads on bone [8]. We hypothesize that existing skinsuit technology can be

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leveraged to produce a comfortable countermeasure garment that exerts a static loading regime on the wearer equivalent to that on Earth. Such a suit could replicate the gradual increase in Gz loading to a significantly greater resolution and comfort than current countermeasures, while also permitting enhanced impact loading when worn as a harness and integrated with existing exercise devices. The aim of this pilot study is to describe a conceptual Gravity Loading Countermeasure Skinsuit (GLCS), and investigate the skin pressures theoretically required to generate a normal static loading regime. Prototype suits will be produced and flown on a microgravity parabolic flight to conduct limited preliminary operational tests of the GLCS, such as donning/doffing ease, temperature effects, comfort, mobility and material strain/load performance. Possible physiological benefits beyond bone protection will also be discussed.

2. Countermeasure suits

2.1. Pingvin suit

The Russian Pingvin (or Penguin) Suit is one of the current countermeasures utilized on the ISS. It is a muscle and bone loading suit for use in microgravity that induces weight bearing stresses on the skeleton and resistive exercise to the musculature [16,17]. Upper and lower body loading along the vertical axis (z-axis) are imposed by bungee cords above and below a leather belt: from the shoulders to the belt (upper body), and from the belt to the feet (lower body) [17]. The upper body can be loaded up to 40 kg, with this load transmitted to the whole body if the belt is loose [13,18]. If the belt is tightened so that it does not slip downwards, more load can be applied to the lower body by shortening the leg cords. The suit therefore creates permanent compression along the z-axis for skeletal maintenance, and resistance to the normal postural position for weight bearing muscle stimulation. The calf muscles are loaded by cords to the boots, which have been found to preserve the condition of the soleus during a 2 month bed rest [19]. Cosmonauts have found the suit to be very hot, and have cut the bungee cords as the 1- or 2-stage loading is highly uncomfortable. Despite use since the 1970s and Russian faith in the device, the effectiveness of the suit in preserving bone mass has not been quantified as no dedicated ground-based trials have been performed. There is no reliable inflight data, as the suit is used in conjunction with other countermeasures, and the uncalibrated bungee straps are adjusted individually for comfort [13,16,17,20].

2.2. A gravity loading countermeasure skinsuit

2.2.1. Concept

Previous skinsuits for space use (also known as mechanical counterpressure, or MCP suits) are designed to pressurize the astronaut during EVA. Compression of approximately 222 mmHg is imposed on the skin to duplicate the pneumatic pressure of current NASA gas-pressurized EVA suits, and is achieved with high tension in the circumferential fibres of the garment around the body part [21]. In contrast, the conceptual GLCS would impose weight bearing loading by gradually increasing tension in the z-axis fibres, with very low tension circumferentially to stop suit slippage. It has been found in previous skinsuit research that various magnitudes of material strain are possible at different parts of the body, as a friction with the skin stops the material from uniformly stretching [21,22]. Just as the Pingvin suit has a leather belt that allows for a 2-stage garment, the GLCS uses each circumferential fibre of the elastic weave as a 'belt' to produce many vertical stages. This design allows a significantly finer stepwise resolution in simulating the 1 g loading regime on the body. Further, the loading difference above and below each circumferential fibre is very small; the required skin pressure to stop each fibre from slipping axially should therefore be significantly lower than the single belt of the Pingvin.

2.2.2. Design

As the arms are not normally subject to any weight bearing (and suffer negligible skeletal loss during spaceflight), the GLCS should supply loading only to the torso and legs as a sleeveless garment. For the suit material, a bi-directional elastic weave was chosen to achieve the different longitudinal and lateral tensile requirements. Fibres would be orientated with high stiffness or modulus in the z-axis, E_z, so that substantial bodyweight forces could be created without overstretching the weave, particularly in the lower body. Conversely, low modulus fibres would be used circumferentially, E_{circum}, to facilitate easy donning/doffing, and so that the tension (and hence applied skin pressure) would not vary significantly due to changes in body shape (such as through movement or microgravity-induced fluid shift). The GLCS would require no power, create no noise or vibration, and have minimal volume and mass. Nominally, the suit would apply the full bodyweight at the feet via shoes and stirrups to spread the load over the entire sole to mimic standing. Stirrups could also be used to harness the suit to exercise or vibration devices. The porous nature of elastic weave garments allows for normal auto-thermoregulation, while some classes of elastic actively wick perspiration away from the skin. Crewmembers may be able to exercise, work normally or even sleep while wearing the countermeasure suit, in accordance to a wide variety of possible wearing protocols.

3. Method

3.1. Loading characteristics

3.1.1. Static loading

The basic static loading regime experienced on Earth must be known as baseline data, so that it can be simulated by the GLCS. Skeletal static loading for all points on the z-axis can be calculated by summing the weight of all superior body segments. Segment mass has been widely researched and published in the literature, and can be found for humans of various physical differences (e.g. gender, age and race) as a percentage of total body mass. In this pilot study, data from Churchill et al. [23] and different gender studies from Plagenhoef et al. [24] were chosen according to subject characteristics. Using this body segment data, loading could be calculated at the shoulder, hip, knee, ankle and sole of the foot. The continuous loading regime was estimated by linearly interpolating between these calculated values.

While the GLCS garment extends over – and applies force to – the shoulders, the loading can only begin to increase where the horizontal fibres can form a full circumferential 'belt' around the body to prevent slippage. To avoid restriction of shoulder and arm movement, this full circumferential region commences just under the armpits, and continues down to the ankles. In the design shown in Fig. 1, the load at the shoulders is considered to be the load at the armpits; this leads to higher loads at the shoulders, but the torso is never underloaded. An option is to reduce or even normalize the load at the shoulders, permit underloading to the armpits, and engineer the suit to increase the loading rate, so that it would normalize by the hips. Similarly, a design option exists at the ankles, where again full circumferential loops are not practical around the foot in the horizontal plane. In the present design, the loading gradient on the shank is increased so that the total 1 g loading is achieved at the bottom of the shank; this allows for a full 1 g load at the soles of the feet.

3.1.2. Skin pressure calculations

A primary design goal of the GLCS is to minimise the 'belt' skin compression required for the elastics to attain variable strain fields and duplicate the static loading regime. As compression decreases, physical discomfort to the wearer is reduced, while donning/doffing ease is improved. Skin pressure, p, is equal to the normal force N divided by area A, but is also described by the hoop tension equation for a thin walled cylinder

$$p=\frac{N}{A}=\frac{T}{r} \tag{1}$$

where T is the circumferential material tension and r is the body segment radius. For this study, the suit is considered to be a series of stages along the z-axis, each requiring a unique vertical loading (to mimic the normal 1 g loading regime at that location), and hence skin pressure to maintain position. The height of each stage of the skinsuit, h, is equal to the spacing between the circumferential fibres of the material, and Area A under each stage is therefore equal to the local body circumference multiplied by the stage height, or $2\pi rh$. Using this data and Eq. (1) to solve circumferential material tension

$$T=\frac{Nr}{A}=\frac{N}{2\pi h} \tag{2}$$

The resistance of the suit to sliding up and down is related to friction forces F, equal to the coefficient of friction between the elastic and skin μ multiplied by the normal force N. For the GLCS, F represents the axial force trying to displace the suit, and is the difference in loading above and below the stage. F is prescribed as the rate of change in the 1 g loading regime, rather than the absolute loading at that the z-coordinate. The normal force N is the force applied by the material on the skin. The friction coefficient, μ, thus relates the skin compression, N, required to prevent the stage slipping under the force F. Continuing to solve for tension yields the following:

$$T=\frac{F}{2\mu\pi h} \tag{3}$$

We can also solve for skin pressure by incorporating the hoop tension Eq. (1)

$$p=\frac{F}{2r\mu\pi h} \tag{4}$$

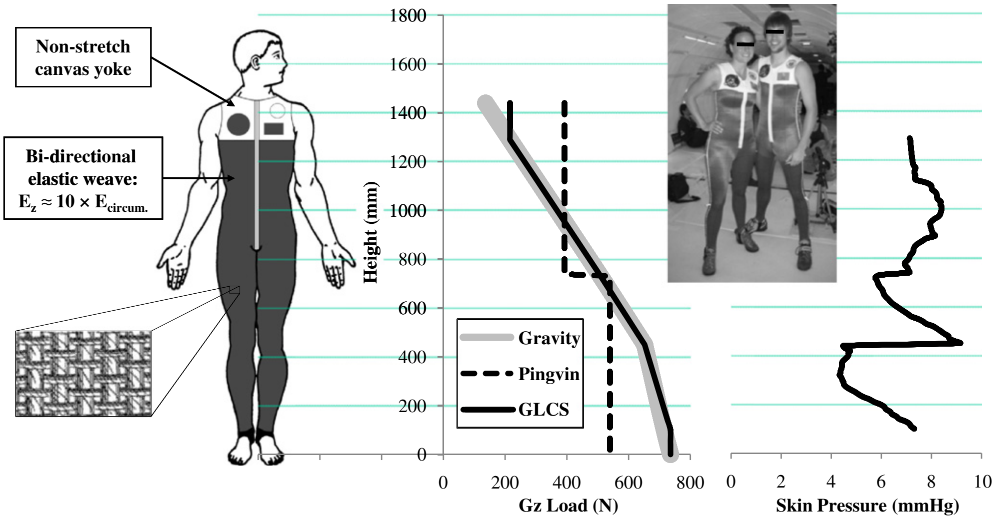

Fig. 1. Gravity loading countermeasure skinsuit (GLCS) with loading regime and skin pressure for Subject 1 (1.7 m, 75 kg). Inset: GLCS prototypes worn during parabolic flight tests.

Body segment circumference and average radius could be accurately obtained from the subjects by direct measurement at each 10 mm height of the torso, thigh and shank. These values were used in Eq. (4) to determine the skin pressure along the *z*-axis.

3.2. Prototype evaluation

3.2.1. Pilot flight study

A number of prototype suits were required to study practical aspects of the suit (such as mobility, comfort and material performance), and to explore if similar operational criticisms of the Pingvin suit were apparent in the GLCS. A parabolic flight would permit accurate determination of weightless material strains, mobility hindrance and donning/doffing ease without the weight and/or friction artifacts of standing or lying in 1 g. The GLCS prototype study was performed on a flight campaign of 20 parabolas operated by Zero-g Corporation (Vienna, VA). During hypogravity portions of the flight, each suited subject was photographed in three sections (torso, thigh and shank) to visually determine the vertical material strain, and hence imposed vertical loading. A seamstress tape was held against the garment during photography as a length reference. The practicality of the suit was explored via a survey of the subjects immediately post-flight. This subjective data collection studied don/doff ease, mobility hindrance, comfort and thermal properties. Comfort was measured using a modified Corlett and Bishop discomfort scale, shown in Table 1 and rated from 1 to 10 with 1 being the most desirable [25]. Also shown is the Cooper-Harper scale, using the same 1–10 rating, which is used to determine the level of compensation a person feels is necessary to maintain body control [26]. The Corlett and Bishop and Cooper-Harper ratings have been used to gauge comfort and mobility hindrance in previous spacesuit studies [27,28]. The pilot study was performed under an existing protocol approved by the MIT ethics review board.

Table 1
Modified Corlett and Bishop discomfort and Cooper–Harper body control scale.

Rating	Discomfort	Body control (mobility)
1	Nude comfort	Unrestricted
2	Pyjamas, 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 control lost

3.2.2. Subject selection and fabrication

The prototype suits were required to be professionally fabricated to a standard adequately robust for the rigors of the study protocol, and sufficiently accurate to allow for justified iterative design improvements in the next development phase. Costumeworks (Boston, MA) were selected to produce the prototypes due to their close proximity (which would be an advantage for multiple fittings for each subject) and prior experience in producing custom garments with bidirectional elastics.

Three suits could be produced within the time and budget constraints of the pilot study, which allowed for a limited study of three subjects due to the highly custom nature of the skinsuit. Subjects were chosen from a pool of applicants according to availability and willingness to participate in multiple suit fitments and the parabolic flight, with consideration to vary gender, height, weight and age as much as possible. Table 2 shows details of the three selected subjects, and informed consent was obtained from each participant.

After analysis of the longitudinal and lateral material strains required for the subjects, a commonly available anisotropic elastic weave was found to be suitable with an E_z, approximately ten times greater than E_{circum}. The coefficient of friction between the elastic and skin was derived by dragging an elastomeric coupon loaded with different weights (or *N* values) across the skin of the prone subject. The force required to move the weights was recorded by a spring weight gauge (measuring *F*), and the coefficient determined by Eq. (4) to be 0.55. Height and circumference anthropometrics of the subjects, together with the warp and weft material properties, minimum skin compression and loading regime data, allowed for the calculation of the necessary vertical and circumferential strains required of the suit at each measured vertical resolution of 10 mm. This strain map allowed standard unitard tailoring patterns to be modified and reduced in size, so that the suit matched the subject's size after the required vertical and circumferential stretch. The yoke (or shoulder region) was fabricated in non-stretch canvas, so that the armpit elastic line (and commencement of load graduations) was consistently located and could not migrate downwards due to inconsistent shape and stretch over the shoulders. Stirrups were also attached at the ankles to apply loading to the soles of flight shoes, and incoporated a webbing-type squeeze clip to help with donning/doffing. Non-stretch ribbons along each neutral side axis of the body ensured that the spandex could not exceed the design strain, and were spot sewn at regular intervals, according to the flat pattern strain configuration. These stretch arrestor ribbons had finger loops to

Table 2
Selected subjects.

	Subject 1	Subject 2	Subject 3
Age	32	24	24
Gender	Male	Female	Male
Height (m)	1.70	1.68	1.81
Mass (kg)	75.0	63.5	72.6

assist with donning, much like cycling gloves have in the finger crotches for doffing. A front zipper was also used to assist in donning/doffing. Horizontal lines were drawn on the unstretched suit at regular intervals, so that the strain could be observed and calculated, when worn in the stretched condition.

4. Results

The normal loading regime of gravity and required skin pressure was calculated for all three subjects. Table 3 shows that the loading regime – starting from the shoulders – begins at 136.9, 113.0 and 145.9 N for subjects 1, 2 and 3, respectively, and increases to their bodyweight at the soles of the feet. Torso, thigh and shank skin pressures required of the suit to prevent axial slippage were calculated, with mean values of 7.5, 6.3 and 4.8 mmHg, respectively. Skin pressures for all subjects were between 4 and 10 mmHg and are shown in Table 3 (mean ± SD). The findings for Subject 1 are shown graphically in Fig. 1, which compares the normal gravitational loading regime with the GLCS and maximum Pingvin suit loading. Required GLCS skin pressure is also shown.

All three subjects wore their GLCS prototype for at least the duration of the parabolic flight. Total donned duration was approximately 3.5, 5 and 5.5 h for subjects 1, 2 and 3, respectively. Subject 3 required donning assistance with the yoke, but the other subjects stated that donning was easily accomplished in less than 1 min. Doffing was easily accomplished by all subjects. None of the subjects noted any abnormal temperature effects, while wearing the GLCS. Strain photographs were taken twice for each subject; however, images of the torso of Subject 3 on the second sweep were not focused sufficiently for measurements. On an average, comfort was rated at 5 (too uncomfortable to wear all day), and mobility at 2 (negligible impact). The torso, thigh and shank observed strains were 100.8%, 96.5% and 61.5% of the required design strains. Table 3 also lists the mean and individual discomfort and mobility survey results, and observed *z*-axis strains (mean ± SE).

5. Discussion

5.1. Prototype design and production limitation

The aim of this pilot study was to describe the concept of the GLCS, conduct skin pressure modelling, and conduct initial feasibility and operational studies of the first prototype design. Only three subjects could be tested, all donning the GLCS, within the schedule and financial limitations of the program. Despite the range in subject characteristics, the limited cohort size means that the flight study results are presented as positive initial findings of prototype performance, and cannot be interpreted as conclusive findings for a GLCS. However, the prototypes were sufficient to produce substantial data on design improvements, such as the number and position of the stretch arrestor ribbons, yoke assembly/bordering, suitable skin pressure strategy, stirrup placement and integration with flight shoes, donning/doffing methods, initial sizing techniques and unitard template modifications. Future designs will need to address the implications of multi-day use such as washing requirements and highly robust materials. Adjustment may need to be incorporated to accommodate material strain degradation and body shape changes over time.

5.2. Skin pressure

As pressure is not required from a suit during intravehicular activity (IVA) in a vehicle/habitat, skin compression for the GLCS should be minimal for comfort and donning/doffing purposes. The skin pressure for all subjects is between 4 and 10 mmHg and varies directly with the loading gradient and inversely with the local body segment radius. For example, the sudden reduction in pressure at the knees is due to the significant reduction in loading rate for the shank compared to the thigh. The GLCS skin pressures are similar to tight socks, and less than form-fitting athletic garments and flight socks that compress at 14–17 mmHg [29], or maternity hosiery at 15–20 mmHg. Compression of this magnitude has been found to provide circulation and thermoregulation gains [30], while also providing metabolic, performance and

Table 3
Calculated Gz loading, required skin pressure, and parabolic flight results of discomfort, mobility and material strain for each subject.

	Subject 1	Subject 2	Subject 3	Mean
Shoulders Gz load (N)	136.9	113.0	145.9	131.9
Hips Gz load (N)	504.7	393.3	474.4	457.5
Knees Gz load (N)	651.8	539.8	624.0	605.2
Ankles Gz load (N)	715.2	606.4	691.6	671.1
Soles Gz load (N)	735.8	623.0	711.9	690.2
Torso skin pressure (mmHg)	7.6 ± 0.5	6.7 ± 0.8	8.3 ± 0.6	7.5 ± 0.9
Thigh skin pressure (mmHg)	7.1 ± 1.1	6.3 ± 1.1	5.6 ± 0.8	6.3 ± 1.2
Shank skin pressure (mmHg)	5.3 ± 1.0	5.1 ± 1.0	4.3 ± 0.9	4.8 ± 1.0
Comfort (1–10)	7	4	4	5
Mobility (1–10)	2	2	2	2
Torso *z*-strain (%)	98.9 ± 9.1	101.3 ± 8.9	103.6 ± 1.8	100.8 ± 4.8
Thigh *z*-strain (%)	71.7 ± 7.8	120.2 ± 4.9	97.7 ± 5.7	96.5 ± 5.9
Shank *z*-strain (%)	44.9 ± 3.0	84.1 ± 6.7	55.5 ± 6.0	61.5 ± 5.0

endurance improvements during exercise [31]. As the leather belt of the Pingvin is approximately 40 mm in width (derived via inspection of Pingvin schematics in Severin [17]), the skin pressure would be approximately 50 mmHg for the presented loading regime, which returns loading to normal at the hips. Physiologically, the tolerable limit of localized overpressure for several hours is between 40 and 50 mmHg (depending on activity level, age and gender), and may cause a cessation of blood flow or compartment syndrome [32–34].

5.3. *Loading regime*

Despite the necessary design compromises at the shoulders and ankles, Fig. 1 shows that the GLCS may be highly accurate at simulating 1 g static loads. This conceptual design shows approximately normal loading from the armpits to the knees, and also at the soles of the feet, with higher loading over the shoulders and shank. Fig. 1 also shows the Pingvin suit configured to the maximum of 40 kg on the upper body. While this creates a force on the shoulders that is higher than normal or the GLCS (and represents carrying a 25 kg backpack), the load falls below normal at approximately waist level. To return normal loading at the hips, an extra 150 N must be added to the regime at the belt. This new load on the lower body is constant, and does not match the increasing load normally imposed by gravity. For Subject 1, the Pingvin produces a deficit of 196 N (or 27% of bodyweight) at the feet. The goal of the Pingvin is not to mimic gravity loading, as it provides postural resistance to the musculature in addition to bone loading [16,17]. However, this analysis indicates that comfortable and effective 1 g bone loading is not possible with such a 2-stage garment, compared to a skinsuit approach.

The strain measurements taken during the parabolic flight show that overall the suit imposed the required loading on the torso and thigh, but only 61% on the shank. This may be because the stirrups were inaccurately sized too long, allowing the suit ankle to slip towards the knee. Considerable variation was also found in the mean loading of the thigh, with Subject 1 at 72% and Subject 2 at 120%. This may be due to the crotch of the suit slipping, incorrect donning of the suit, or incorrect fabrication of the conformance ribbons. Measurement of strains also involved error due to the reference tape being stretched taut over body segments (instead of conformal to the surface undulations), when the tape was not aligned precisely to the z-axis, and due to parallax issues when subject and photographer occasionally encountered difficulties remaining square to each other during weightlessness.

5.4. *Subjective data survey*

The suit was worn during the parabolic flight with great success, and generally with great comfort and little hindrance to mobility. There was evidence that the suit could be uncomfortable under the armpits (Subjects 1 and 3) and at the knees (Subjects 2 and 3). Pain around the armpit of subject 1 was caused by maladjustment in the shoulder strap in the final fitting, and was the cause of the high discomfort rating of 7. The other subjects rated discomfort at 4, which indicates they would be happy to wear the suit all day (16 hours). Improved sizing and fabrication methods are expected to further reduce discomfort. Irritation at the knees may be caused by those subjects kneeling down to help with other experiments during level flight. All subjects found the suit provided negligible impact on mobility, which indicates the suit would allow for normal work practices and exercise routines when donned. Donning and doffing was easily accomplished by all subjects except for subject 3, who required help during donning. The height of Subject 3 may be a contributing factor in his additional difficulty, but post-flight trials found that donning was easier for all subjects when the suit was correctly stretched vertically to the waist before the torso section was stretched and the yoke placed onto the shoulders.

5.5. *Lunar/Mars GLCS loading requirements*

The deconditioning of astronauts on the Moon or Mars is unknown as there is little data on the response of the skeletal system in a partial gravity environment. It is likely, however, that the reduced gravity loading of these environments will still cause deconditioning, but at a slower rate than purely orbital missions [4,35]. Atrophy in hypogravity environments is particularly relevant for planned lunar colonisation, and proposed Mars missions which include extended surface stays of up to 18 months. Future GLCS designs could be adjustable to complete the loading not provided by the respective planetary gravity fields, and thus continue to function as a countermeasure. As the GLCS loading regime would only impose 0.84 and 0.62 g for the Moon and Mars, respectively, skin compression requirements would also be reduced. The GLCS is ideally suited to long-duration interplanetary missions, as skinsuit attributes align with the countermeasure requirements imposed by new exploration-class spacecraft, such as limits on mass, volume, power, noise and vibration [36].

5.6. *Static and dynamic loading*

It is likely that an artificial loading regime that mimics normal exposure on Earth may be optimal for bone maintenance on future exploration missions [3–5,8]. The most fundamental skeletal loading condition in 1 g is caused by the static weight of the body, and is of greatest magnitude when standing. This static loading varies along the z-axis, as the load at any point is equal to the bodyweight above it: the load at the shoulders is therefore equal to the weight of the head and arms, and gradually increases to the full bodyweight at the soles of the feet. Further loading is caused by impact forces and muscle activation from locomotion. Osteogenesis is commonly believed to be initiated when peak dynamic forces cause skeletal strains that exceed a threshold value [9,37]. However, static loading has been shown to protect bone as short periods of standing during bed rest can significantly reduce calcium excretion [37]. Further, patients with spinal cord injuries lose considerable skeletal mass in the lower extremities, but maintain it in the lumbar spine due to gravitational loading in the wheel chair [9]. Recent theories suggest that a loading ‘dosage’ may be more relevant in reducing and predicting bone loss, and confirm that both static and dynamic loads should be duplicated by an effective countermeasure system during microgravity exposure [13,18,38,39].

The GLCS can independently supply only static loads, but it is designed to integrate with other exercise countermeasures to improve the magnitude and comfort of impact load delivery. For cycle ergometers (such as the currently used CEVIS) and steppers (perhaps with inbuilt ‘thumpers’), the GLCS stirrups could be placed around and underneath the pedals, and therefore pull the astronaut down at full bodyweight. Similarly, the suit could apply vibration plates to the soles of the feet at 1 g, replicating earth-like protocols, where the subject stands on the plates at full bodyweight.

Treadmill exercise loading and comfort could be improved by modifying the GLCS torso to function as a harness. An extra 1 g force would be applied at the hips (where the treadmill straps are fastened), but this load can be distributed over the large surface area of the upper body, rather than just the shoulders and hips of a traditional harness. To accommodate this extra harness loading, modelling shows that skin pressure on the torso could increase to 29 mmHg, or about the average level of medical compression garments. This additional chest pressure is not expected to inhibit breathing, as respiratory muscles of adult males and females have been found by Lausted et al. [40] to produce an average maximum inspiratory pressures of 131 and 89 mmHg, respectively. The harness can be added as a separate torso garment, or incorporated into the suit via a secondary zipper that tightens the torso section as required.

5.7. Further benefits

Beyond bone preservation, the GLCS may also serve as a countermeasure to spinal elongation and associated lower back pain. Normal static loading of the suit may inhibit disc height growth and connective tissue strain, and preserve lumbar lordosis and normal spinal curvature [15]. Mechanical stimulus on the soles of the feet may provide proprioceptive stimulation and reduce sensorimotor deconditioning. Layne et al. [41, p243] notes that “foot pressure may be useful for facilitating neuromuscular activation throughout the course of a spaceflight, thereby perhaps attenuating muscle atrophy and the associated postflight motor control deficits experienced by crewmembers”. The mild compression on the torso and legs might also combat post-flight orthostatic intolerance.

Astronauts can also suffer from disorientation, motion sickness, a loss of sense of direction and loss of posture stability. Upon return to Earth, astronauts can experience problems standing up, stabilizing their gaze, walking and turning, and retaining posture. The magnitude of sensorimotor disturbances after gravity transitions increases with microgravity exposure, which is of particular relevance to long duration spaceflight [42]. Such disturbances are expected to significantly impact operational activities, including approach and landing, docking, remote manipulation, extravehicular activity and egress (both normal and emergency), and thus compromise crew safety, performance and mission success. It is believed that this sensorimotor deconditioning results from inflight adaptive changes in central nervous system processing of information from the visual, vestibular and proprioceptive systems [43,44]. The absence of muscular proprioception has been shown to affect performance in several ways, and plays a key role in determining the spatial motor frame of reference [45]. The loss in postural control has also been attributed to atrophy of the antigravity extensor muscles and spindle sensitivity [46].

5.8. Future studies

In the present study, the mass density of body segments was assumed to be homogenous, so the normal gravity loading regime was determined by linear interpolation between the calculated loads at the shoulders, hips, knees and soles of the feet. Future studies could improve accuracy between these calculated points by including intra-segmental mass distribution data from scanning studies, such as Bauer et al. [47] and Durkin and Dowling [48]. It will also be necessary to understand the transmission and tolerance of vertical load to the skeleton through local soft tissue compression and shear.

In the short term, pressure arrays will be inserted into the GLCS shoes to confirm that the normal force distribution over the soles of the feet when standing (measured with the stirrups disconnected) can be replicated by the suit, when the subject is lying down (stirrups connected). To give an indication of physiological impact, studies will also compare the height increase during nocturnal, supine sleep of subjects with and without the GLCS as pyjamas. Investigations will also explore local skeletal loading dosages (i.e. $N \cdot h$), and the benefits, designs and wearing protocols of a suit that imposes this normal dosage regime, rather than just 1 g.

6. Conclusion

The GLCS is a promising concept to reduce physiological deconditioning (particularly skeletal) on future long duration missions. It may significantly improve the static and dynamic loading of astronauts to sustained 1 g levels with no power or noise, and minimal volume or mass, while also resisting painful spinal elongation, and providing neuromuscular stimuli. This pilot study showed that the GLCS may be a practical garment for spaceflight, with good comfort, mobility, thermal qualities and donning/doffing ease indicated by the preliminary studies on three initial prototypes. Crewmembers may be able to work normally, exercise or sleep, while wearing the suit. A critical factor in the promising feasibility of the suit is the very low required skin compression, found to be equal to (or less than) commonly worn athletic garments. Prototype GLCSs displayed accurate strains on the torso and thigh, but insufficient strain on the shank, which should be addressed in the next design iteration. For future planetary exploration, the GLCS can also be tailored to complete normal loading when worn on the surface of the moon or Mars.

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