Countermeasure Suits for Spaceflight

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In the past decade, there has been a renewed effort to develop countermeasure suits for spaceflight, largely through the Gravity Loading Countermeasure Skinsuit, or "Skinsuit". Upcoming missions to the moon and Mars, will require unprecedented lengths of time in reduced gravity and necessitate further consideration of countermeasures to address physiological adaptations to reduced gravity during missions of several months or years. While countermeasures for bone and muscle loss currently exist on the International Space Station (ISS) in the form of exercise machines, these do not completely eliminate the debilitating effects of microgravity, and they are too large and massive for long-duration missions to Mars due to expected vehicle physical space constraints. Wearable countermeasures could address this problem by providing alternative or supplementary countermeasures. The Pingvin suit, developed in the 1970s, is a wearable countermeasure suit that aims to reduce muscle and bone loss in cosmonauts. However, it is often ineffective due to discomfort and the resulting inconsistency in wearing protocols. The Skinsuit is a more recent development in wearable countermeasure technology. This skin-tight garment provides an axial load on the skeleton to simulate the skeletal loading provided by gravity, with goals to reduce spinal elongation and bone loss, among other proposed advantages. The Skinsuit has evolved through multiple design revisions to ensure comfort, mobility, and feasibility for extended periods of wear. The function of the suit has also been tested through ground experiments, partial gravity analogs, parabolic flights, and ISS missions. This paper provides a comprehensive review of the Skinsuit and briefly highlights the Russian Pingvin Suit, the Dynasuit, the Torso Compression Harness, and the Variable Vector Countermeasure Suit.

Nomenclature

ABL	=	Axial Body Loading
ARED	=	Advanced Resistive Exercise Device
BMD	=	Bone Mineral Density
BR	=	Breathing Rate
ECG	=	Electrocardiogram
EMG	=	Electromyogram
ESA	=	European Space Agency
HR	=	Heart Rate
ISS	=	International Space Station
iRED	=	Interim Resistive Exercise Device
IVA	=	Intravehicular Activity
IVD	=	Intervertebral Disk

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GLCS	=	Gravity Loading Countermeasure Skinsuit
HBF	=	Hyper-Buoyancy Flotation
RPE	=	Rating of Perceived Exertion
TCH	=	Torso Compression Harness
VTF	=	Verticalized Treadmill Facility

I. Introduction

In prolonged exposure to microgravity, the mechanical load on the human body significantly decreases, leading to physiological changes and deterioration. The musculoskeletal system experiences bone mineral density (BMD) loss, muscle atrophy, and spinal elongation[1–4]. Resistive and aerobic exercises are used as countermeasures to reduce microgravity-induced deconditioning. While exercise countermeasure machines are currently in place on the International Space Station (ISS), these do not fully eliminate musculoskeletal effects. The resulting deterioration of performance levels and increased risk of injury can compromise astronaut health and their ability to perform vital tasks during future exploration missions, particularly after the long journey in microgravity (~8 months) to reach Mars, not to mention the 1.5-year return mission to Earth.

Additionally, large exercise countermeasure equipment may not be feasible for future spaceflight, due to expected vehicle physical space constraints during Mars missions[5]. Modified exercise devices will likely be required to satisfy the constraints for smaller spacecraft. The use of alternative countermeasures, such as pharmaceuticals, electrical stimulation, or wearables, may prove useful to supplement exercise during future missions to the moon and Mars and to further attenuate musculoskeletal effects in current ISS mission scenarios. Several wearable countermeasures have been designed and tested for spaceflight, most notably the Pingvin suit and the more recent Gravity Loading Countermeasure Skinsuit (GLCS or Skinsuit), both of which have a primary aim of providing musculoskeletal loading. Wearable countermeasures provide a versatile option to address multiple physiological changes during spaceflight and can be worn during daily activities or used to augment exercise.

II. Relevant Space Physiology

Bone responds to mechanical loading and applied strains[6]. Consequently, a loss of typical axial loading on the skeleton, as experienced in reduced gravity, can lead to bone loss, particularly in weight-bearing areas such as the lower spine and lower extremities[2]. Previous experiments show that approximately 1% to 1.5% of BMD, a measure commonly used to indicate fracture risk, was lost in the spine, femoral neck, trochanter, tibia, calcaneus, and pelvis every month in microgravity, despite the use of exercise countermeasures[1,2,7]. The average rate of BMD loss in microgravity exceeds typical rates seen in post-menopausal women, and during a 4- to 6-month mission on the ISS, the loss of proximal femoral strength reaches approximately half of the expected lifetime loss of bone strength in Caucasian females[8,9]. The introduction of the Advanced Resistive Exercise Device (ARED), which replaced the original Interim Resistive Exercise Device (iRED), provided significant improvements in maintaining BMD; however, there remain variations across individuals[5,10]. Additionally, markers of bone resorption remain increased post-flight with ARED use, suggesting that the typical use of BMD may be inadequate for measuring bone loss[11]. Beyond the dynamic loading experienced during exercise, the benefit of static loading on bone has been demonstrated on Earth through decreased calcium excretions with periods of standing during bed rest[12] and spinal maintenance in wheelchair-bound individuals[13]. Long term conditions may also result from spaceflight-induced bone loss, such as early-onset osteoporosis[8,9]. Bone loss also causes increased calcium excretion, which can lead to the formation of renal stones[2,14,15]. In longer missions, renal stones could be life-threatening if treatment or timely transportation to Earth is not available.

Stature can increase by up to 7 cm in microgravity[16], which may cause pain and discomfort in astronauts in addition to long-term health concerns[4]. Back pain is reported by 52% of astronauts[17], and the risk of disc herniation after return to Earth is 4 times that of the average individual[18]. While the exact mechanisms are largely unknown, bed rest studies indicate that intervertebral disk (IVD) expansion and the loss of spinal curvature may contribute to spinal elongation, and it is suggested that the atrophy of trunk muscles may contribute to a decrease in spinal curvature and stability[4,19]. Exercise is currently the only loading countermeasure for spinal elongation, and it is unknown what risks could be presented by dynamic loading on a weakened spine[4]. While the mechanistic underpinnings of in-flight and post-flight back pain and injury still require further study, astronauts may benefit from static loading countermeasures to prevent the prolonged unloading of the spine during spaceflight[4].

Muscle atrophy varies with different muscle locations. Antigravity muscles, such as lower limb extensors and back muscles, are often most affected, as these muscles maintain the body's posture while standing in 1G. In microgravity, the body no longer needs to maintain an upright posture, and thus, these muscles are largely unused[2]. Slow-twitch muscle fibers, characterized by high endurance levels, are highly prevalent in postural antigravity muscles and are more affected by microgravity than the rapidly fatiguing fast-twitch fibers[2,15]. During long-duration ISS missions (Expeditions 1-25), mean isokinetic muscle strength in the knees, ankles, and trunk was reduced by 8% to 17% of preflight values. While some improvements in post-flight muscle strength were seen in participants using the ARED compared to participants using the iRED, there were no statistically significant differences[20]. After return to Earth, most muscle strength is recovered within a month, with 1% to 9% residual deficits[20].

Unloading in microgravity also affects body-load receptors[21] and causes changes in proprioception[22]. In combination with adaptations in the vestibular system, these sensorimotor adaptations may affect posture, locomotion, balance upon return to Earth[2,22]. In addition to the use of exercise countermeasures to re-introduce body loading[22], studies suggest that foot pressure or plantar stimulation in microgravity may enhance neuromuscular activation and attenuate neuromuscular degradation[23,24]. Muscle activation patterns are known to change in microgravity relative to preflight measurements, including, for example, decreased preparatory muscle activation in the lower limbs[25,26]. By re-introducing foot pressure in microgravity using special pneumatic shoes, muscle activation in the lower limbs was enhanced during arm raises compared to a control condition with no foot pressure[24].

III. Countermeasure Suits

Five countermeasure suits were identified that target the musculoskeletal system. Of these, three were in conceptual or early prototyping phases, two were tested in-flight, and one, the Pingvin suit, has been used regularly as a spaceflight countermeasure. However, evaluations of Pingvin suit quantitative performance and qualitative comfort metrics during flight are lacking in the literature. The Skinsuit has recently been flown on the ISS, prompting a review of its success thus far.

A. The Russian Pingvin Suit

The Russian Pingvin (or Penguin) suit has been used by Russian cosmonauts since the 1970s. The suit uses bungee cords to provide longitudinal compression and resistance against normal posture to encourage muscle activation. The bungee cords are anchored to a belt around the waist, which allows for 2 loading stages: the shoulders to the belt and the belt to the feet (Fig. 1). If the belt is loosened, these can be combined to one stage from the shoulders to the feet[27–30]. The Penguin-3 suit can reportedly achieve approximately 50% bodyweight loading at maximum tensioning over 6 to 8 hours per day[29]. A load measuring system was implemented in the suit in 2007, using tension dynamometers connected to the bungee cords[29]. However, quantitative results using this equipment are not reported in any accessible publications.

Calf muscles are also targeted using a set of bungee cords from the shin to the boots to induce plantar flexion (Fig. 1). During 2-month-long bed rest testing, the plantar flexion loading of the Pingvin suit was shown to maintain the contractile properties of soleus muscle slow-twitch fibers[31]. Additional benefits of the Pingvin suit include increased venous return caused by muscle activation in the lower legs[15]. The Pingvin suit may also restore feedback from mechanoreceptors in the skin and muscles, potentially providing a sensorimotor benefit[32]. Higher energy efforts are also required to overcome the resistance of the Pingvin suit's bungee cords, which can serve to compensate for the lack of energy used during daily activities in microgravity[27].

While the Penguin-3 suit was regularly used by Mir cosmonauts, it is used much less frequently on the ISS, except by taller cosmonauts. Tall crewmembers may have a higher risk of not fitting in their Soyuz seats after stature changes due to microgravity, and they typically wear the Pingvin suit during their last month on the ISS in order to address stature changes[33,34]. The suit was also modified to develop the Adeli suit for cerebral palsy, which is used for therapy applications on Earth[35].

Figure 1. The Russian Pingvin Suit (from Kozlovskaya et al., 2004)

Despite its claimed advantageous countermeasure features, the Pingvin suit is reported to be uncomfortable. Cosmonauts have been known to cut the bungee cords to relieve discomfort, thus rending the suit non-functional[28]. The Pingvin Suit belt would require approximately 50 mmHg of skin pressure to produce the appropriate loads, likely reaching the tolerable limits for localized pressure before peripheral nerves are acutely jeopardized[28,36]. In a subjective review of in-flight physical training for 12 ISS cosmonauts, it appears that only 4 cosmonauts regularly wore the Pingvin suit and received adequate loading[37]. However, formal comfort and usability studies have not been published. In-flight, the Pingvin suit is used in combination with other countermeasures and bungee cords are self-adjusted: uncontrolled variables that have prevented the collection of reliable in-flight data. Additionally, quantitative assessments of the Pingvin suit's effect on the skeletal system, including bone loss and spinal elongation, are not reported in the literature[28].

B. The Gravity Loading Countermeasure Skinsuit

The Skinsuit is an intravehicular activity (IVA) suit that was developed to simulate the effects of Earth's gravity by applying a static load on the body using material tension. Similarly, to the Russian Pingvin suit, axial body loading (ABL) is applied from the shoulders to the feet; however, the Skinsuit uses elastic material in the form of a skin-tight wearable suit, which is designed to include hundreds of vertical stages, rather than 2 stages as in the Pingvin suit[28,38]. With higher loading resolution, the Skinsuit aims to provide countermeasure loading with greater comfort and accuracy than previous countermeasure suits. First published in 2011 by researchers at MIT, the initial results of the Skinsuit were promising, showing comfort rated for multiple hours[28]. Later work by MIT and King's College London confirmed that the Skinsuit can be used in conjunction with physical exercise, allowing the potential to supplement current exercise countermeasures[39–41].

1. *Design and Fabrication*

Skinsuits are custom-sized for each individual. A bi-directional elastic weave allows ABL to be applied by tension in the longitudinal direction, while circumferential tension provides skin pressure to anchor the longitudinal fibers. Low circumferential stiffness assists in donning and doffing and allows the suit to be less sensitive to changes in circumference, such as those due to breathing, movements, or microgravity-induced fluid shifts[28,42].

A sleeveless non-stretch canvas yoke provides an anchor point at the shoulders, and load is transferred to the feet using stirrups under the soles of the shoes. The arms are regularly used for ambulation in microgravity and are not load-bearing

Figure 2. Skinsuit evolution from MKI to MKVI (Includes images from Kendrick, 2016 and Costume Works Inc.)

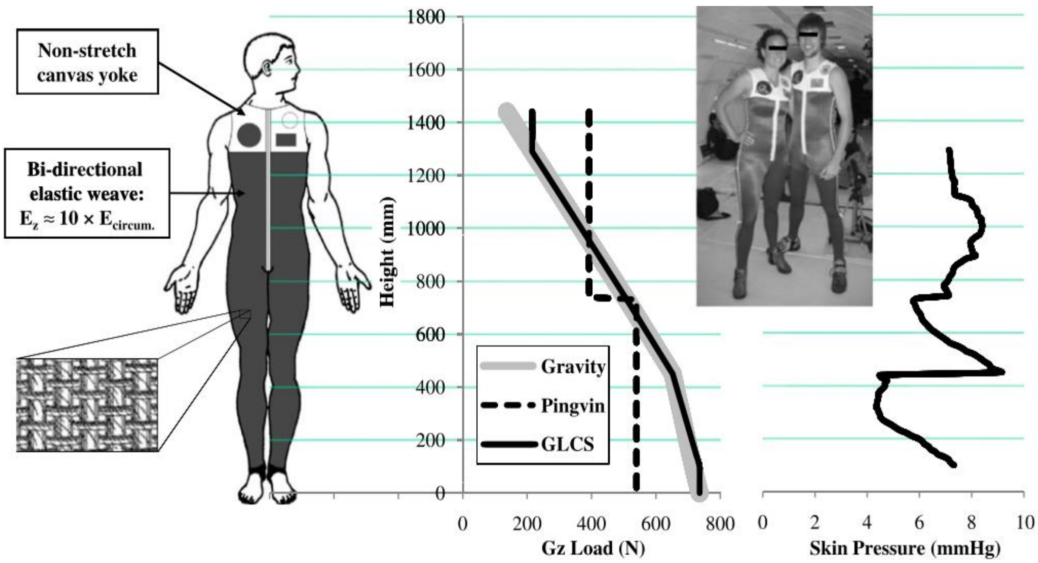

Figure 3. The calculated Skinsuit axial loading regime and skin pressure for one participant (from Waldie and Newman, 2011).

bones on Earth. Thus, the arms do not experience significant levels of bone or muscle loss and are not targeted by the suit. Non-stretch ribbons, referred to as stretch arrestor ribbons, are sewn at regular intervals along the length of the suit to ensure that intended strain is not exceeded and to provide loops to assist in donning and doffing. A zipper is included on the front, side, or back of the suit: a feature which has been adjusted throughout Skinsuit development to assist in donning and doffing[28,42]. Several versions of the suit have been developed in the past decade which include modified suit features (Fig. 2)[42].

2. Loading Regime Model

The Skinsuit's required longitudinal material tension is determined by calculating the loading regime of an individual's body in 1G. The estimated load is calculated for each body segment using anthropometric data, and values are interpolated to provide a continuous estimation. In Figure 3, a calculated Skinsuit loading regime is compared to the calculated loading regime of gravity and the Pingvin suit. Using an increased loading resolution, the Skinsuit aims to more accurately simulate the pattern of gravity loading compared to the Pingvin suit[28]. The calculated Skinsuit loading regime closely follows 1G loading except for increased loading at the shoulders and shank which compensate for the discontinuity of circumferential fibers above the armpits and below the ankle[28]. However, experimental loading regimes are typically much lower than the 1G target. These results are further discussed in section IV.A.

Skin pressure is required to prevent slippage of the suit material and to anchor the loading stages. Circumferences are measured along the vertical height of an individual's body at a specified resolution (usually every 1 or 2 cm)[28]. The hoop tension equation, described in Waldie and Newman, 2011, is then used to determine the skin pressure and corresponding material tension sufficient to resist displacement by longitudinal forces. Required skin pressures are typically less than the skin pressures provided by athletic compression garments (14 to 17 mmHg) (Fig. 3)[28].

C. Other Countermeasure Suits

Three other countermeasure suits were investigated; although, none have published human testing or in-flight experiments. The concept for ESA's Dynasuit was proposed in a paper in 2012, but no further realization of this idea is publicly documented. Dynasuit is presented as an active intelligent suit with bio-sensors and actuators (electro-active polymers or pneumatic) in a biofeedback loop. Dynasuit features include movement resistance, ABL, and foot sole stimulation. Proposed sensors for the Dynasuit include body position, electromyography (EMG), heart rate (HR), electrocardiography (ECG), body temperature, ventilation rate, blood pressure, and oxygen saturation[43].

Sayson et al. mention the Torso Compression Harness (TCH) to prevent spinal deconditioning. The TCH provides loading to produce extension in the spine, intending to induce compensatory spinal flexion, activate core muscles, and enhance spinal stability. Images of a TCH garment are provided by Sayson et al., but no records of experimental tests or quantitative data are provided[44].

Lastly, the Variable Vector Countermeasure Suit (or V2 Suit) concept aims to provide "viscous resistance" against a selected "down" direction during movements. This resistance aims to attenuate sensorimotor deterioration, with future versions potentially targeting bone and muscle. A wearable kinematic system with inertial measurement units is employed to track movements, which informs the resistance produced by actuating control movement gyroscopes. While an algorithm for down tracking has been developed, several obstacles remain before bringing the V2Suit to an operations phase, including the miniaturization of gyroscope components to suit wearable applications[45,46].

IV. Evaluation of the Skinsuit

A. Skinsuit Loading

The MKI Skinsuit loading regime was evaluated during a parabolic flight with 3 healthy participants in custom-made suits. The suits were marked with horizontal lines before donning, and the material strains in the longitudinal direction were recorded with photographs to provide an indirect measurement of ABL. The mean longitudinal strain provided at the torso, thigh, and shank was 100.8 (± 4.8) %, 96.5 (± 5.9) %, and 61.5 (5.0) % of the intended strain, respectively, with variations across participants[28].

ABL in the MKIII Skinsuit was assessed for 8 participants using pressure sensors on the soles of the feet and the shoulders. The Skinsuit provided 0.7 (± 0.3) G at the feet, decreased from the intended 1G. Variations across participants were attributed to suit fit or adjustments, such as stirrup length[40]. The load at the shoulders was also measured to demonstrate the gradient of load across the body. The shoulders showed significantly lower pressure readings than the feet with 0.1 (± 0.1) G[40]. The MKVI Skinsuit resulted in much lower loads at the feet with a range of 0.07G to 0.24G[47,48]. Despite the very large error between theoretical and experimental values, loading levels near 0.2G were considered acceptable for spinal elongation experiments and helped to improve comfort[49]. A loading level of 0.2G ABL was expected to provide stature effects based on a study that showed approximately 6mm and 5mm of stature reduction after 20 minutes of carrying a 15% bodyweight load with anterior and posterior loading, respectively[50].

B. Comfort, Mobility, and Donning/Doffing

During a variety of Skinsuit experiments, qualitative metrics were collected. A modified Corlett and Bishop discomfort scale was used to measure comfort[51], and the Cooper-Harper body control scale was used to measure mobility hindrance (Table 1)[52]. Ratings of perceived exertion (RPE) were also obtained using Borg's scale (Table 2)[53]

Preliminary parabolic flight results with the MKI indicated that, in the context of tolerability, the suit could be prescribed in multiple-hour doses, but not for the entire day (Table 3)[28]. Ground testing with the MKIII Skinsuit collected qualitative metrics during resistive and aerobic exercise to ensure that the Skinsuit would be compatible with current exercise countermeasures[40,41]. The suited condition showed significantly decreased comfort and body control compared to an unsuited control in all resistive and aerobic activities[40,41]. However, RPE scores did not show significant changes during resistive exercises, except during the shoulder press (Table 3). All participants were able

Table 1. The modified Corlett and Bishop discomfort scale and the Cooper-Harper body control scale (Waldie and Newman, 2011)

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 control lost

Table 2. Borg's RPE Scale (Borg, 1982)

Rating	Perceived Exertion
6	None
7 - 8	Very, very light
9 - 10	Very light
11 - 12	Fairly light
13 - 14	Somewhat hard
15 - 16	Hard
17 - 18	Very Hard
19 - 20	Very, Very Hard

to perform 12 repetitions for each resistive exercise, except for the shoulder press[40]. The functional ability to perform most exercises seemed unimpaired by the Skinsuit, despite the effects of comfort and limitations in range of motion[40]. The MKIII was tested again during supine ergometer exercise with a 6-degree head-down tilt as an analog for microgravity conditions. Ratings for suited cycling varied per participant, with one participant providing an overall discomfort rating of 3, while the other participant provided a rating of 7. However, the latter participant rated both cycling conditions (suited and unsuited) as a 7, indicating that the participant was uncomfortable with the supine ergometer, rather than the suit itself[39]. Later studies used Hyper-Buoyancy Flotation (HBF) as a microgravity analog, allowing participants to remain in a supine position, similarly to bed-rest studies, but on a waterbed with hypersaline water to promote buoyancy[49]. 8-hour HBF testing with the MKVI Skinsuit showed improved ratings for comfort and body control, perhaps due to suit design improvements, lower ABL, or the lack of physical activity during testing (Table 3)[47]. Across different body parts, comfort in the MKI and MKIII was often rated lower in the yoke area and the knees; improvements to fit and fabrication were cited as possible solutions[28,39].

Published ground testing for the MKIII Skinsuit assessed joint range of motion (ROM) in 8 participants at the shoulder, spine (yoke and T12), knee, and hip. All measured joints show significant decreases in ROM, except for shoulder extension and hip adduction (Table 4)[40]. The shoulder and upper spine were likely hindered by the Skinsuit yoke[40]. A sit-and-reach task also showed a significant decrease in reach distance, and a get-up-and-go task took a significantly longer period of time while wearing the Skinsuit[40]. The MKV Skinsuit includes shoulder yoke modifications; however, complete range of motion tests in the MKV or MKVI have not been published.

Table 3. Skinsuit Comfort, Mobility, and Exertion

Reference	MK	Environment	Activity	n	Mean Discomfort		Mean Body Control		Mean RPE	
					unsuited	suited	unsuited	suited	unsuited	suited
[Waldie & Newman, 2011]	I	Parabolic Flight	Non-specific, 3-6 hours	3	-	5^n	-	2^n	-	-
[Carvil et al., 2016]	III	Ground	Shoulder Press	8	2	8*	2	7*	15	16*
			Squat	"	2	7*	2	6*	15	15.5
			Chest Press	"	2	6*	2	5*	15	15
			Seated Row	"	2	5.5*	2	5*	15	15
			Leg Press	"	2	5.5*	2	5*	15	16
			Calf Raise	"	2	5*	2	5*	13.5	15
[Attias et al., 2017]	III	Ground	Upright Cycling	8	3.4	7.3*	2.5	5.8*	13	15.4*
[Diaz Artiles et a1., 2016]	III	Ground	Rest, Non-specific	2	-	4^n	-	-	-	-
			Supine Cycling	"	4.5	5^n	-	-	-	-
[Green et al., 2015]	VI	Ground/HBF	8-hr HBF	8	0.9	1.4	0.6	1.2	-	-
[Carvil, 2017]	VI	Ground/HBF	8-hr HBF	9	0.5	2.5^n	2	2.5^n	-	-
			8-hr HBF	6	4	4^n	3.5	4^n	-	-
			8-hr HBF	8	2	5*	1.5	4*	-	-
			Reloading after 8-hr HBF	8	2	4*	1	3*	-	-
[Attias, 2018]	VI	Ground	Rest, Seated on Ergometer	8	2.2	3.7*	1.5	3.2*	7.2	7.0
			$VO_{2,Max}$ Upright Cycling	8	2.5	4.2	2.3	4.2	17.5	15.8*

* $p < 0.05$ for unsuited-suited comparison, ^{n} significance not reported

Table 4. MKIII Skinsuit Joint Range of Motion (n = 8) (Carvil et al., 2016)

	Spinal Flexion at yoke (°)	**Spinal Extension at yoke (°)**	**Spinal Flexion at T12 (°)**	**Spinal Extension at T12 (°)**	**Shoulder Flexion (°)**
Unsuited	143 ± 5	33 ± 3	82 ± 3	33 ± 3	183 ± 6
Suited	105 ± 7*	21 ± 6*	56 ± 3*	11 ± 1*	149 ± 8*
	Shoulder Extension (°)	**Hip Abduction (°)**	**Hip Adduction (°)**	**Knee Flexion (°)**	**Knee Extension (°)**
Unsuited	65 ± 4	60 ± 7	26 ± 3	113 ± 4	12 ± 1
Suited	51 ± 9	48 ± 6*	26 ± 5	100 ± 3*	11 ± 1*

* $p < 0.05$ for unsuited-suited comparison

Donning and doffing tests in early MKI experiments report donning times of less than 1 minute; however, some participants reported difficulty with suit donning during both MKI and MKIII testing[28,40]. Efforts to improve donning processes include the addition of a back zipper, similar to a wetsuit, which was implemented starting in the MKIV. Results of donning tests with this modified zipper have not been published. Across all Skinsuit studies, assessments of thermal comfort very rarely have significant differences between suited and unsuited conditions[40,41,47]. An assessment of skin microbiota during ground testing and an ISS Skinsuit experiment showed some changes in skin microbiota during MKVI Skinsuit wear, but these were determined to be acceptable and unlikely to affect the health of the skin microbiome[54].

C. Effects on Cardiorespiratory Performance Measures

Aerobic exercise testing with an ergometer was performed by 8 participants wearing the MKIII Skinsuit in 1G. Ventilatory responses (including VO_2, VCO_2, and V_E) were significantly increased during the first 5 minutes of cycling in the Skinsuit; however, they began to plateau to match unsuited values after 20 minutes of cycling[41]. MKIII testing showed no significant differences in heart rate (HR), breathing rate (BR), or core temperature between suited and unsuited conditions[39,41]. However, MKVI testing showed increases in HR and a steeper BR/minute ventilation ($\dot{V}_E$) slope, indicating more rapid and shallow breaths[48]. VO_{2Max} tests with the MKVI Skinsuit show that aerobic capacity is unaffected by ABL but can be reached with less work and time[48]. In further studies, reloading to 1G with the MKVI Skinsuit in simulated reduced gravity did not return affected cardiorespiratory measures to normal 1G levels, except for respiration rate[48]. In MKIII testing, significantly greater blood lactate levels were observed in suited conditions compared to unsuited conditions, even after 20 minutes, which may indicate anaerobic metabolism[41]. One study additionally reports a change in the HR-VO_2 relationship; however, this mechanism is not yet understood[41].

D. Effects on Stature and Back Pain

Nonsignificant decreases in stature were first seen during a 1G exercise session with the MKIII Skinsuit in 5 of the 8 participants. These stature changes were isolated to the spine, as there were no observed height differences between the calcaneus and iliac crest in these participants[40]. In an experiment with 8 participants, 8-hour HBF was used as a microgravity analog. A statistically significant attenuation of spinal elongation was seen with the MKVI Skinsuit (+1.8 cm) compared to an unsuited control condition (+2.4 cm)[47]. Additional non-significant attenuations in spinal elongation were seen in further MKVI HBF studies[49]. A Skinsuit experiment during an ESA ISS mission also showed a partial reversal of stature increase, but the mechanism of this attenuation remains to be investigated[4].

To assess its reloading effects, the Skinsuit was donned after spinal elongation was induced with HBF. Following 8 hours of unsuited HBF, participants donned the MKVI Skinsuit. Mean stature was immediately and significantly reduced to 178.2 (± 7.8) cm with the Skinsuit, compared to 179.2 (± 7.7) cm without the Skinsuit. When placed in HBF for 4 more hours after this reloading, only 0.3 mm of spinal elongation was observed over the 4 hour period[49]. In a similar study, reloading with the Skinsuit after 8 hours of unsuited HBF reduced mean stature gain by 50% compared to an only 30% drop in stature gain with unsuited reloading[49].

To analyze the mechanism of spinal elongation attenuation, the spine was imaged during MKVI testing. After 8 hours of HBF, results showed some decreased IVD heights in the lumbar region for Skinsuit conditions compared to the unsuited control[49]. In other studies, significant IVD height changes were only seen in the thoracic and cervical regions[49]. In separate tests, IVD height in the lumbar region was insignificantly decreased with Skinsuit reloading after 8 hours of unsuited rest in HBF[49]. There were no significant differences in spinal curvature associated with Skinsuit wear. However, one study showed insignificant increases in lumbar curvature, with minor individual increases in 4 of the 6 participants[49].

MKVI HBF experiments showed non-significant decreases in back pain ratings[47,49]. In one study, only 2 of the 8 participants experienced cervical pain in suited conditions, compared to 5 participants in the control condition. Suited conditions also had a delayed onset of lumbar pain, compared to the control[47]. During 8-hour unsuited HBF, 2 of 8 participants experienced low levels of back pain, which were alleviated when the Skinsuit was donned[49].

E. Effects on Neuromuscular Activity and Biomechanics

While using a MKVI Skinsuit with approximately 0.2G loading on Earth, therefore producing 1.2G total ABL, there were no significant changes in EMG root mean square amplitude or median frequency in lower limb muscles, including the vastus lateralis, rectus femoris, biceps femoris, tibialis anterior, lateral gastrocnemius, medial gastrocnemius, gluteus maximum, and soleus[48]. Partial gravity simulations showed that a 0.2G change in bodyweight offload (1G to 0.8G or ~0.36G to 0.16G) during unsuited running did not provide changes in EMG magnitude, except in the vastus lateralis[48]. This makes it difficult to assess any EMG magnitude changes due to Skinsuit reloading in partial gravity simulations and also indicates that the 0.2G loading of the MKVI Skinsuit may not be adequate to affect EMG activity. Additionally, no significant increases in vastus lateralis EMG magnitude were seen during Skinsuit wear in simulated 0.16G on the Verticalized Treadmill Facility (VTF) compared to the unsuited 0.16G control[48].

While no changes in amplitude or frequency were observed, some changes in muscle activation pattern occurred with Skinsuit wear. During 1.2G loading with the Skinsuit, an increased duration of muscle activation was observed in the lateral gastrocnemius and the soleus, which are both antigravity muscles[48]. Some changes in biomechanics were observed during running with the Skinsuit in 1G, including reduced knee flexion at heel strike and reduced maximum knee flexion during swing, which may be due to the range of motion restrictions of the Skinsuit[48].

V. Discussion

A. Skinsuit Usability

Skinsuit comfort evaluations while resting or supine indicate that the suit can be worn for multiple hours, with some participants indicating that it would be comfortable if worn all day. Comfort results during exercise indicate that MKIII Skinsuit wear during exercise would likely be comfortable for at least 2 hours, with some variation across participants and activities. Mobility results indicated that body control deficits were tolerable across all activities. While exercise provided statistically significant decrements in comfort and mobility compared to unsuited controls, the ability to perform exercise was not impaired. With the exception of the shoulder press, all aerobic and resistive tasks were completed successfully, and RPE did not increase significantly during resistive exercises. Additionally, expected improvements in donning/doffing time for the MKVI Skinsuit have not yet been published.

Ground experiments were performed to further test the Skinsuit's usability during exercise. The augmentation of ventilatory parameters by the Skinsuit was not a surprising result, as net work is increased with the resistance of the suit's fabric, which must be stretched to allow movement. This effect has been seen previously in the Pingvin suit[27]. Overall, the transient nature and low magnitude of ventilatory changes observed during Skinsuit wear are not sufficient to impair the ability to perform prolonged submaximal exercise[39,41]. However, cardiorespiratory performance has yet to be tested in microgravity. The only published results from ISS testing detail the Skinsuit's effect on the skin microbiome, showing these changes to be acceptable[54].

One notable limitation of all published Skinsuit studies is the small sample size. Due to the custom nature of the Skinsuit, the ability to fabricate multiple suits is a continual limitation. Additionally, the type of control condition should be considered when assessing Skinsuit comfort, as all controls used standard, loose-fitting clothing. Direct comparisons with the Pingvin suit have not been performed, and this comparison may be more relevant when assessing the Skinsuit as a loading garment[40].

B. Skinsuit Function

While the Skinsuit's ability to reduce stature can be observed by hyper-loading in 1G, assessing its more operationally relevant ability to attenuate spinal elongation requires an appropriate analog environment, such as HBF. HBF experiments with the Skinsuit have shown spinal elongation attenuation, but in some cases, the attenuation has been statistically insignificant. While 0.15 bodyweight load carriage has been shown to provide stature changes[50], the optimal Skinsuit ABL should be further investigated to determine the wearing protocols and ABL levels required to affect spinal elongation.

Cardiorespiratory investigations tested the Skinsuit's ability to augment exercise in reduced gravity. Results show that Skinsuit reloading in reduced gravity exercise does not return reduced cardiorespiratory performance parameters to normal 1G values. Attias hypothesizes that this may be due to skin compression[48], as compression tights are shown to reduce energy cost while running[55]. The effects of compression (without securing the Skinsuit stirrups) should be investigated to determine its contribution to cardiorespiratory changes[48].

No published experiments have investigated the direct effects of the Skinsuit on BMD loss or muscle atrophy, as these require long-term investigation in microgravity or an appropriate analog. Thus, we cannot yet compare the Skinsuit to the Pingvin suit in terms of muscle maintenance. Neuromuscular activation studies, however, show that 0.2G ABL has little effect on muscle activation, despite hypothesized effects. However, observed changes in muscle activity duration during Skinsuit wear may indicate changes in movement control strategies. Increased resistance to knee flexion during Skinsuit wear was also validated with computational modeling[42,56]. Decreases in knee flexion during Skinsuit wear were seen through biomechanical analysis[48], and the Skinsuit's effects on muscle activity during flexion and extension movements should be further investigated. Additionally, low levels of ABL may not provide observable reloading effects during Skinsuit wear, and Attias suggests that there may be an optimal level of Skinsuit ABL to encourage increased muscle activation[48]. For example, unsuited tests in different levels of bodyweight suspension showed that a ~0.2G change in ABL did not provide changes in EMG amplitude. This introduced limitations in the study, where some participants received a change in ABL of only 0.07G between the suited and unsuited conditions[48]. ABL level should be investigated to determine an appropriate dose that is both physiologically beneficial and achievable through the Skinsuit design. Additionally, sensorimotor effects of the Skinsuit have not yet been evaluated in microgravity. The inherent pressure applied to the soles during Skinsuit wear may provide beneficial afferent stimulation to prevent neuromuscular deterioration during spaceflight[24].

ABL was assessed for the MKIII and the MKVI Skinsuit using pressure sensors on the soles of the feet. The resulting loads varied across Skinsuit versions and individuals, ranging from 0.07G to 0.7G. Future work should consider more reliable loading materials for Skinsuit fabrication to produce higher levels of ABL and determine an appropriate and achievable loading dosage. Skinsuit fabric strain can be used as an indirect measurement of load at intermediate points on the body to assess the function of the suit as a multi-stage garment with a loading gradient. As seen in the initial MKI Skinsuit parabolic flight, strains were as expected in the torso, but dropped to approximately 60% of the intended value at the shank. The authors suggested that the decreased strain seen in the shank could have occurred due to inaccuracies in stirrup placement or sizing[28]. These previous measurements were taken by visually assessing the strain of the fabric. This method is prone to errors if photographs are misaligned and does not allow for real-time measurements of fabric strain. To obtain more reliable and real-time measurements, wearable strain sensors can be integrated into the Skinsuit, as previously prototyped in Stoppa's doctoral thesis[57]. In addition to strain sensors, wearable pressure sensors could provide integrated, real-time load data. Load monitoring can assess the function of the suit and additionally track the daily loading that an astronaut receives, providing data to inform the prescription of countermeasures. This is especially relevant, as the ARED cannot monitor ground reaction forces due to a sensor failure after delivery to the ISS. Built-in load monitoring capabilities could also have applications in informing adjustments to the Skinsuit. Carvil et al. recommend a system that provides real-time feedback on ABL to allow for adjustments during flight, accounting for problems with suit donning adjustments, posture, or in-flight changes to anthropometry[40]. Further, the Skinsuit could be leveraged as a "smart suit" to track astronaut performance levels and health. Potential measurable parameters include HR, ECG, respiration rate, body temperature, activity level, EMG, and kinematics[58].

VI. Conclusion

Multiple ground and flight tests have supported the viability and usability of the Gravity Loading Countermeasure Skinsuit. With comfort rated for multiple hours and no impairment in most resistive and aerobic exercises, the Skinsuit provides a suitable supplement to current exercise countermeasures. During supine HBF, the comfort of the MKVI Skinsuit has been rated near equivalent to pajamas in some participants, suggesting that the Skinsuit could be leveraged to provide static loading during sleep; several overnight HBF experiments showed that participants were able to sleep while wearing the Skinsuit. Additionally, significant ABL and spinal elongation attenuation have been accomplished with Skinsuit wear. While the Skinsuit may not be sufficient as an independent countermeasure to mitigate spaceflight adaptations, the suit is compatible with current exercise countermeasures and could be used to enhance or supplement exercise. ISS experiments, currently unpublished, have encouraged continued Skinsuit development by ESA, MIT, and other collaborators. Future work includes the continual investigation of the Skinsuit's effects on the human body, the investigation of a physiologically optimal and functionally attainable ABL dosage, and the integration of wearable technology to produce a "smart" countermeasure suit. Additional applications on Earth may include use in populations with motor control disorders[59], paralleling the evolution of the Adeli Suit for cerebral palsy from the Russian Pingvin suit. The goal of the Skinsuit is to enable humans to adapt to multiple levels of gravity, bringing us one step closer to long-term space habitation, while also providing technology for rehabilitation on Earth.

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