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The effect of the gravity loading countermeasure skinsuit upon movement and strength

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ABSTRACT

Introduction. Effective countermeasures against musculoskeletal de-conditioning induced by microgravity and disuse are required. A simple alternative to provision of artificial gravity by centrifugation, is compressive axial loading, the Russian "Pingvin" suit was the first wearable suit to apply this concept, using bungee cords, tethered, around the shoulders and feet. However, poor loading characteristics, severe thermal and movement discomfort were reported. The gravity loading countermeasure skinsuit (GLCS) uses a bidirectional weave to generate staged axial loading from shoulders to feet, better mimicking how Earth's gravity induces progressive loading head to foot. The Mk III GLCS's loading was evaluated and tolerability assessed during maximal joint motion, ambulation and selected strength exercises. **Method**. Eight subjects (5 male and 3 female; 28±3yrs; 179±0.1cm; and 74.8±2.9kg) having given written informed consent, had a Mk III GLCS individually tailored. Axial loading imparted, body height, joint range of motion (ROM), ambulation and strength tests (12-rep max) were performed in the GLCS and gym attire (GYM), with subjective (RPE, thermal comfort, movement discomfort and body control) ratings recorded throughout. **Results.** GLCS provided significant axial loading when standing but significantly reduced knee (-13^{o}), spinal (-28^{o}) and shoulder flexion/extension ROM (-34^{o}/-13^{o}), in addition to sit and reach (-12.8cm). No thermal issues were reported but there was an increase in subjective discomfort. GLCS did not significantly impede strength exercise, with the exception of shoulder press (15.7±4.1 vs. 18.4±3.4 kg). **Conclusion.** The GLCS (Mk III) demonstrates potential as a countermeasure by providing tolerable, static axial loading. Furthermore, it may serve as a elastic-like strength exercise adjunct, which may have utility as a rehabilitation modality after further design refinement.

Key words: Gravity; resistance training; disuse; vertical compression; ambulation

INTRODUCTION

Muscle atrophy and bone demineralisation can be induced by unloading, whether through disuse due to injury or illness (1) physical inactivity (2) ageing (3) or exposure to microgravity (4). These, and associated cardiovascular deconditioning (5) are high priorities for both space agencies and public health organisations as amelioration would improve functionality, quality of life, and reduce injury and mortality risk on Earth, and in space. While acute responses to microgravity (< two weeks) appear to be moderate and reversible on return to Earth (5); longer term adaptations present serious risks, following prolonged space missions (4,6). Bone demineralisation and loss of optimal structural architecture are particularly evident in locations that are typically weight-bearing such as the lumbar spine and trabecular head (2). Therefore, there is an increased fracture risk on re-exposure to gravity (4,6).

Furthermore, microgravity-induced muscle atrophy bears some similarities to age-related muscle loss or sarcopenia (3,7). Consequently, the deleterious effects of microgravity exposure have led to it being termed an 'accelerated form of ageing' (4). Such muscle loss is predominantly observed in the postural muscles, with the gastrocnemius and hamstrings atrophying by approximately 20%, after more than three months in space or terrestrial bed rest (9). The ability to generate power in the lower limbs (maximal explosive power; MEP) has also been documented to be effected by microgravity, with one astronaut documented to have reduced MEP during vertical jump testing by 67% after 21 days in space (10).

As a result, resistance in addition to functional (aerobic) exercises are major features of the astronaut health maintenance system (4) with emphasis upon 'anti-gravity' muscles as little muscle atrophy and bone demineralisation of the arms has been noted (11). Typically, NASA and European astronauts complete four to six treadmill, two to three cycle , and six resistance exercise sessions per week (12). However, this extensive countermeasure regime has to date failed to completely protect against microgravity-induced physiological de-conditioning (13). Furthermore, current countermeasures require significant power, volume, mass and crew member time (14). Therefore, a new generation of more effective but low resource intensive countermeasures are required.

Provision of gravity-like axial loading has obvious appeal with hyper gravity, via centrifugation being proposed as a countermeasure during long term space flight (6), to combat either disuse pathology or as a rehabilitation strategy on Earth (9). However, significant engineering and physiological issues such as motion sickness need to be overcome (14). A 'simpler' approach is to provide static axial loading to the body. The Russian TNK V-1 Pingvin or "Penguin" suit which uses bungee cords around the shoulders and feet tethered to a central waist belt provides significant axial loading during walking (15) and around 70% body weight during treadmill running (16). Cosmonauts that adhered to treadmill exercise, with the penguin suit experienced attenuated lumbar vertebrae bone mineral density loss (0-3%), compared to non-adherer's (6-10%) (17). Furthermore, wearing the suit for 10 hours a day with 10kg loading during bed rest preserved Soleus muscle size (18). However, anecdotal reports suggest the Pengvin suit imposes significant thermal and movement discomfort, rendering it inappropriate to be worn for prolonged periods or during exercise. In fact, the majority of cosmonauts refuse to don their suit (19) even though integration with resistance training could reduce both the required workload and length of sessions (16). Such discomfort may originate from the fact that the penguin suits loading regime creates pressure points, as it pulls from the central waist belt, to the shoulders and feet, which is not how the body is loaded on Earth, where when standing, segmental axial body weight loading occurs as result of the pull of Earth's gravity (1Gz; 20).

The gravity loading countermeasures skin suit (GLCS) has recently been developed utilising lightweight (<500g) elastic, porous, bidirectional weaves, in order to better replicate the cumulative nature of axial loading as experienced on Earth (19-20). Axial loading is progressively increased via material tension in the vertical axis fibres (with circumferential tension sufficient to prevent suit slippage). It uses each circumferential fibre of its elastic weave as a "belt" to produce numerous vertical stages; from the shoulders to the feet. Stirrups wrapped around shoes (or insoles) distribute the pressure across the sole.

Pilot studies with the first iteration of the GLCS (mark 1) were tested using the parabolic flight analogue to simulate microgravity conditions, it was determined that there was a negligible impact on mobility when wearing the GLCS and skin pressure was similar to wearing tight socks (4-10mmHg; 20). However, while material stretch was assessed to calculate loading during the flight, actual axial loading experienced by the participant was not determined and it is unknown whether the GLCS is tolerable during ambulation, daily task performance or resistance exercise. Therefore the aim of this study was to assess axial loading provided by a newly designed SkinSuit, the Mk III GLCS and thus determine whether the additional axial loading provided by the GLCS affects tolerability and joint range of motion, perceived exertion, ambulation tasks and resistance exercise performance.

Methods

Experimental Approach to the Problem

Three sessions were conducted within a seven day period with the first session comprising: suit axial loading assessment, familiarisation of joint motion and ambulation tests, and the determination of each subject's (safe) 12 repetition maximum (12 RM) for six selected resistance exercises in loose fitting gym clothing by completing several sets of each exercise with increasing weight whilst their technique was carefully monitored (experimenters were qualified fitness instructors). In the subsequent two sessions, the entire test battery was repeated, on one occasion when wearing the GLCS, and again at least 48 hours later when wearing gym (GYM) clothing, this order was randomised and balanced.

Subjects

Due to the number of GLCS's available, eight young healthy participants were recruited (5 male; 26±3yrs; 182±0.1cm; and 76.8±6.7kg & 3 female; 32±4yrs; 170±0.1cm; and 71.3±4.5kg) and gave written informed consent to participate in the study which received local ethics committee approval. All denied taking any medication or having a history of neurological, cardiorespiratory and/or psychological disorders. None of the participants were in pain, or knew/suspected that they were pregnant. Participants were instructed to abstain from vigorous exercise and alcohol for at least 24 hours and from caffeine for at least two hours prior to each session. Testing took place in a quiet, thermoneutral environment (~23^{o}C; ~32% humidity).

Procedures

All participants were provided with a custom-fabricated gravity loading countermeasure skin suit (Costume Works Inc, Boston, Massachusetts, USA) which necessitated circumferential measures every 2 cm vertically, from the top of the ankle to the yoke (roughly armpit level) for each subject. Sizing was performed twice to ensure accuracy with a linen tape measure.

When participants had donned their suits they were visually checked to ensure that the bottom of the suit was resting in line with the top of the ankle, as the material strain of the suit had been calculated from this point to the yoke line, based on the previous GLCS research (19-20)

Axial loading was determined via Tekscan (F-Scan, USA) pressure sensor insoles inserted *underneath* the shoulder straps, and *between* the sole of the foot and the shoes (flat rigid soled trainers to distribute the pressure) with GLCS foot straps fixed around the shoe. TekScan sensors were calibrated with known weights prior to testing. Two measures were taken, once with the subject wearing the GLCS and shoes but not strapped (i.e. not loaded), to get BASELINE loading, then again when the GLCS ankle straps were looped around the foot and clipped, thus stretching the material and inducing the loading. Bilateral pressure measurements were obtained for 6 seconds when standing upright, with arms relaxed by the sides (n=8). Total pressure (Newton/m^2) when wearing the GLCS, was recorded at foot and the shoulder. Loading recorded when wearing the GLCS was then expressed as an average difference (Δ) from the BASELINE (without GLCS attached; 1Gz)

Total Gz – BASELINE Gz = GLCS Gz.

Height was measured using a standiometer (Cambridge measuring systems, UK) when participants had donned the suit and at the end of the experiment, subjects were asked to stand shoulder width apart during measurement and to fix their gaze forward. Joint flexibility (maximal range of motion; ROM) was determined bi-laterally from three attempts (with measures taken from the best stable attempt) via a bubble Inclinometer (Medical Research Ltd, UK) during: knee flexion/extension, hip abduction/adduction, shoulder flexion/extension and spinal flexion/extension (at both the yoke line and T12, when standing). Back flexibility was assessed via Sit and Reach (22) testing where participants sat upright on a level surface, with straight legs and bare feet flat against the vertical surface of a Sit and Reach Board. Subjects reached forward as far as possible on three occasions with the furthest attempt recorded. Participants were timed performing the Get Up and Go test (23) which required rising from a seated position, walking around a stationary cone (3 metres away), and returning safely to the seated position, as quickly as possible.

Participants performed three sets of 12 repetitions of each exercise :Dumbbell Shoulder Press and Squat (Free weights, Reebok, China), Machine Chest Press and Seated Row (Multigym, Bodycraft, Taiwan), Horizontal Leg Press (Laying leg press, Technogym, Italy) and Seated Calf Raise (Ultimate workout, Nottingham, UK) at their pre-determined 12 RM with breaks of one minute between sets and three minutes between exercises. Technique was observed with improper or incomplete movement leading to exercise termination and the number of completed reps, per set, recorded. Core body temperature was monitored throughout with wireless pill telemetry (CorTemp sensor, HQinc, Palmetto, USA). Upon completion of each set, participants rated perceived exertion (RPE; 6 = rest – 20 = maximum effort), thermal comfort (ASHRAE 7-point; 0 = neutral – 3 = hot) (24) movement discomfort (1-nude comfort -10 = too uncomfortable for 10 minutes) (25) and body control (1 = unrestricted -10 = no control) (26) on scales employed to assess space suits (27).

Statistics

Data was plotted to assess normality in SPSS (histogram, boxplots) with tests of normality (Shapiro Wilk's test; SW test). Data are reported as mean ± standard error of the mean (SEM) except for changes in height (mean ± standard deviation) and subjective ratings expressed as median (interquartile range). A paired samples t-test was used to compare the average difference (Δ) of loading produced at the foot and shoulder and the total height and specific height difference between the Calcaneus and Illiac crest were also compared between GYM and GLCS.

As no differences >5^o were observed in joint ROM, the averaged best attempt for each side was compared between GYM and GLCS with student paired t-tests; except for hip abduction ($p=0.02$) and spinal flexion at T12 ($p=0.01$) which were non-normally distributed (SW test) and thus Wilcoxon tests were employed. Student paired t-tests were also used to compare GLCS vs. GYM for Sit and Reach (cm), Get up and Go (s), number of reps completed in the final set (3rd), average time taken for completion of exercise sets (s). Subjective RPE, discomfort, control, thermal comfort and core temperature change (SW's test $p<0.05$), following exercise performance was compared with Wilcoxon non-parametric test. Statistics were performed using Statistical Package for Social Sciences 19.0 (SPSS Inc., Chicago, IL, USA) with statistical significance assumed when $p < 0.05$.

RESULTS

GLCS Loading

The Mk III GLCS provided significant axial loading (ΔGz) in all subjects imparting 0.7±0.3Gz at the feet, significantly ($p<0.005$) greater than that recorded at the shoulders (0.1±0.1Gz- Figure 1).

Figure 1.

The GLCS (178.7±9.6) when standing induced a small non-significant reduction of height in five of the eight participants vs. when wearing GYM clothing (179.7±9.9cm) garments. No difference in height between the Calcaneus and Illiac crest was observed [GYM (66.9±5.1cm) and GLCS (66.9±3.6cm)].

Joint Motion and Ambulation

GLCS significantly ($p<0.05$) attenuated the ROM of all movements except shoulder extension and hip adduction (Table 1). Sit and reach was also significantly impaired whilst Get up and Go time was prolonged with the GLCS.

Table 1.

Strength Exercise

Participants were able to complete the 3 sets of 12 reps for nearly all the selected strength exercises in both attires. The exception was shoulder press, where a mean of nine reps was completed in the last set ($p < 0.05$) when wearing the GLCS (Table 2). This in turn significantly reduced the average time to complete the set of shoulder exercises. Core temperature remained unchanged apart from shoulder press where a greater increase was reported post exercise in the GYM condition.

Table 2.

Subjective Ratings

Significant movement discomfort ($p < 0.01$) and body control impairment ($p < 0.01$) was induced by the GLCS during all resistance exercises (Table 3).

Table 3.

Rating of perceived exertion was significantly ($p < 0.05$) higher during shoulder press (vs. GYM) only (Table 4). No significant differences in thermal comfort were reported.

Table 4.

DISCUSSION

The main findings of the study were that wearing the GLCS (Mk III) provides approximately ~0.7Gz axial loading at the feet, whilst there was a significant reduction in the maximal joint range of motion, this only had a minor encumbrance in the ability to perform resistance exercise. Core temperature and thermal comfort during strength exercise did not differ between attire, though there was a significant increase in movement discomfort and control required to perform the exercises. During the initial trials subjects found donning and doffing the GLCS challenging, especially with getting their shoulders into the garment and tightening the stirrups, however participants noted this became easier with more practice.

The GLCS provided an additional axial load of approximately 0.7Gz, albeit with a broad range (0.53-1.12Gz). Variation in axial loading between subjects appeared not to be dependent upon gender or stature but may relate to inaccuracies in fitting measurements and/or wear of the suit. This range in loading may also be due to differences in stirrup tightening/loosening as once the study commenced no adjustments were made. Having live feedback on what axial loading is being provided might facilitate greater consistency. This is especially important across multiple donnings and where microgravity/immobilisation induced fluid redistribution (28), anthropometric changes (29-30) or exercise could conceivably alter the loading. Furthermore, whilst not explicitly tested the axial loading appears to be dependent upon posture. Thus, ability to adjust axial load with real time feedback, would be advantageous for application in both user groups on Earth and space where astronauts adopt a "neutral" floating (14).

Though significant loading was recorded, it is presently unknown as to what an appropriate static axial load stimulus might be to attenuate musculoskeletal deconditioning experienced in disuse and microgravity, either alone or in combination with exercise (7). Whilst no direct comparison with the Pingvin suit was conducted, the Mk III GLCS appears to induce axial loading not dissimilar to the 70% of the subject's bodyweight reported during running. However, unlike the Pingvin suit, no thermal tolerance issues arose when wearing the GLCS during exercise, presumably due to fabrication with porous material (15, 19). The material tension created by the elastic weaves in the GLCS also creates vertical tension, which is more analogous to the way the body is loaded on Earth, than the bungee cords in the Pingvin suit. This can be observed in the low pressure recorded at the shoulder and increased pressure at the feet, which likely contributes to its improved tolerability during exercise (20).

When wearing the GLCS for an acute period of time (~2h), total standing height was reduced by ~ 1cm, presumably due to the compression on the intra-vertebral disks, as leg length measured from the Calcaneus to the Iliac crest remained unchanged. If confirmed this may be advantageous in mitigating spinal elongation during immobilisation on Earth (31, 32) and when in space, which has been reported to be as much as 7cm (31). Such elongation can be painful and de-habilitating as well as leading to increased risk of disc herniation (31). However in potential future studies focusing on elongation, standardisation of height assessment to improve reliability should be implemented, as gaze stabilisation was only subjectively controlled, this could be improved by placing fixed markers and pointers to reduce error.

Whilst all maximal joint ranges of motion tested were attenuated by GLCS wear it is rare to require the full range of motion during normal daily activity and as subjects reported few difficulties, functional significance appears minor. Timed Get up and Go was slower but from anecdotal reports may have at least in part due to a reluctance to tear the seams of the suit, rather than locomotion impedance per se, this might be a potential limitation and could indicate greater familiarisation with the GLCS is required prior to testing.

The Pingvin suit has been reported to elevate core temperature and induce thermal discomfort during exercise (33). In contrast, the GLCS had no effect upon strength exercise-induced core temperature or thermal comfort in normal ambient conditions (analogous to the international space station (12)). Movement discomfort and body control were significantly increased whilst wearing the GLCS compared to GYM clothes, suggesting the GLCS could be optimised to improve comfort especially near the shoulder. However, it is important to note that comparison with loose fitting clothing is potentially misleading and a limit of this study, thus, direct comparison with the Pingvin and/or another compression garment affecting performance (34-35) would provide a more appropriate comparative model.

The ability to perform resistance exercise was not significantly impeded by wearing the GLCS in the majority of the exercises performed. However, difficulties were encountered when performing the shoulder press, with three individuals unable to complete the prescribed 3 sets of 12 reps whilst maintaining adequate control. This could be attributed to increased effort required by the participant to overcome the loading provided by the GLCS during the standing shoulder press. Whether this additional effort provides a useful adjunct to resistance exercise would require further study, including an assessment of muscle activity. However, all subjects did report that for the same exercise load (GLCS vs. GYM), wearing the GLCS increased the perceived effort. Thus, the axial loading provided by the GLCS, if adjusted to the appropriate level, might provide a training stimulus across a range of joints and, in postures appropriate to the individuals' requirements and capabilities, offering a potential physiological/training augmentation strategy for use in microgravity and terrestrial settings, as reported with the use of whole body compression garments in male athletes (35).

A main limitation of this study is the small, gender unbalanced sample size and therefore more data from additional gender matched groups should be investigated further. Loading also needs to be reassessed with integrated force sensors in the shoes, during different body positions both whilst in contact with the ground and when floating in microgravity, to more accurately capture the axial load produced by the GLCS. The characterisation of loading should also be performed during the exercise, along with measurements of muscle activity and exercise response, as predominantly only subjective measures of performance during exercise were assessed in this first trial. This could then determine if additional axial load during exercise is effecting muscle recruitment, as this could have intriguing applications for modifying training response. However further refinements to the GLCS are suggested to improve comfort, tolerability and the ability to don and doff the garment with ease, as this was an issue for several participants.

This approach of combined wear with exercises such as running and task specific body weight exercises could be investigated to determine if additional axial loading augments athletic training in healthy populations. Additional axial loading in the future may also aid to provide a stimulus for to support bone fracture healing (36) and rehabilitation from musculo-skeletal degradation induced by disuse, disease or injury (7,37) after further investigation.

PRACTICAL APPLICATIONS

The GLCS demonstrates potential as a lightweight, low volume/cost countermeasure against the loss of axial loading in microgravity, by providing static axial loading broadly analogous to Earth. Such axial loading has minor effects on ambulation and range of motion and renders strength exercise 12 repetition maximum completions more challenging, without apparent thermal issues. With the growing rise of smart clothing in athletic disciplines, loading suits primarily designed for use in space may have potential terrestrial benefit as either training augmentation or rehabilitation tools; however more research is required in this area. Thus the GLCS, with further design improvements and future investigations, may provide a useful adjunct to exercise, potentially either by providing a complimentary training modality or through virtue of its static loading, assist in ameliorating musculoskeletal deconditioning associated with space, disuse or injury.

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REFERENCES

1. Meyer K, Samek L, Schwaibold M, et al. Interval training in patients with severe chronic heart failure: analysis and recommendations for exercise procedures. *Med Sci Sports* Exerc 29 (3):306-312, 1997

2. Shackleford L, Leblanc A, Driscoll T et al. Resistance exercise as a countermeasure to disuse-induced bone loss. *J Appl Physiol* 97: 119-129, 2004.

3. Aagaard P, Magnusson PS, Larsson B et al. Mechanical muscle function, morphology and fibre types in lifelong trained elderly. *Med Sci Sports Exerc* 39 (11): 1989-1996, 2007.

4. Williams D, Kuipers A, Mukai C et al. Acclimation during spaceflight: effects on human physiology. *CMAJ* 180 (13): 1317-1323, 2009.

5. Sides M, Vernikos J, Convertino V et al. The Bellagio Report: Cardiovascular risks of spaceflight: implications for the future of space travel. *Aviat Space Environ Med* 76: 877–895, 2005.

6. Young L. Artificial Gravity Considerations for a Mars Exploration Mission. Ann N Y *Acad Sci* 871: 367-378, 1999.

7. Vainiopaa A, Korpeainen R, Kaikkonen H et al. Effects of impact exercise on physical performance and cardiovascular risk factors. *Med Sci Sports Exerc* 39 (5): 756-763, 2007.

8. LeBlanc A, Lin C, Shackelford L, Sinitsyn V et al. Muscle Volume, MRI relaxation times (T2) and body composition after spaceflight. *J Appl Physiol* 89: 2158-2164, 2000.

9. Narici M, De Boer M. Disuse of the musclo-skeletal system in space and on earth. *Eur J Appl Physiol* 111: 403-420, 2011.

10. Antonutto G, Bodem F, Zamparo P et al. Maximal power and EMG of lower limbs after 21 days of spaceflight in one astronaut. *J Gravit Physiol* 5: 63-66, 1998.

11. Sawka M, Pandolf K. Upper body exercise: Physiology and training application for human presence in Space. *S.A.E.Trans* 91: 1-19, 1999.

12. Moore A, Lee S, Stenger M et al. Cardiovascular exercise in the U.S. space program: Past, Present and future. *Acta Astronaut* 66: 974-988, 2010.

13. Layne C, Forth, K. Plantar stimulation as a possible countermeasure to microgravity-induced neuromotor degradation. *Aviat Space Environ Med* 79: 787 – 794, 2008.

14. Lackner J, & DiZio P. Artificial gravity as a countermeasure in Long-Duration Space flight. *J Neurosci Res* 62, 169-176, 2000.

15. Sevrin G, & Svertshek V. Pengvin-3: Muscle and bone loading suit. Moscow: Aviaexport pp. 1-2, 2001.

16. Kozlovskaya I, Grigoriev A, Stepantzov V. Countermeasure of the negative effects of weightlessness on physical systems in long term space flights. *Acta Astronaut* 36: 661-668, 2001.

17. Kozlovskaya I, & Grigoriev A. Russian System of countermeasures on board the International Space Station (ISS): the first results. *Acta Astronaut* 55: 233-237, 2004.

18. Ohira Y, Yoshinaga T, Ohara M et al. Myonuclear domain and myosin phenotype in humans after bed rest with and without loading. *J Appl Physiol* 87: 1776-1785, 1999.

19. Waldie J. Mechanical Counter Pressure Space Suits: Advantages, limitations and concepts for Martian exploration. The Mars Society [internet]. Available from http://www.marspapers.org/papers/Waldie_2005.pdf. 1995 [cited 2013 Feb 10]

20. Waldie J, Newman D. A gravity loading countermeasure skinsuit. *Acta Astronaut* 68: 722-730, 2011.

21. Marwaha V. A current understanding of the various factors of bone loss incorporated into the development of the gravity loading countermeasure skinsuit (GLCS), Dissertation, International Space University, Strasbourg, 2010.

22. Wells K, Dillon E. The sit and reach. A test of back and leg flexibility. *Res Q* 23: 115-118, 1952.

23. Podsiadlo D, Richardson S. The timed 'Up and Go' Test: a Test of Basic Functional Mobility for Frail Elderly Persons. *J Am Geriatr Soc* 39: 142-148.

24. ASHRAE, Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard. New York (USA): The American Society of Heating, Refrigerating, and Air Conditioning Engineers; 1974. 55-74 p.

25. Corlett N, Bishop R. A technique for assessing postural discomfort. *Ergon* 19: 175–182, 1976.

26. Cooper G, Harper R. The use of pilot training in the evaluation of aircraft handling qualities - Technical Report TN D-5153. Houston, TX: U.S. NASA; 1969. Available from: NASA, Houston. pp. 1-52.

27. Vos J, Gernhardt M, Lee L. The walk back test: a study to evaluate suit and life support system performance requirements for a 10km lunar traverse in a planetary suit. *S.A.E.Trans* 116: 194–206, 2007.

28. Hargens A, Richardson S. Cardiovascular adaptations, fluid shifts, and countermeasures related to space flight. *Respir Physiol Neurobiol* 1: 1-30, 2009.

29. Greenleaf J, Bernauer E, Juhos L et al. Effects of exercise on fluid exchange and body composition in man during 14-day bed rest. *J Appl Physiol* 43 (1): 126-132, 1977.

30. Bergouignan A, Momken I, Schoeller D et al. Regulation of energy balance during long-term physical inactivity induced by bed rest with and without exercise training. *J Clin Endocrinol Metab* 95 (5): 1045-1053, 2010.

31. Sayson J, Lotz J, Parazynskic S et al. Back pain in space and post-flight spine injury: Mechanisms and countermeasure development. *Acta Astronaut* 86: 24-38, 2013.

32. Kalb R, Solomon D. Space Exploration, Mars, and the nervous system. *Arch Neurol*. 64: 485-490, 2007.

33. Kozlovskaya I, Grigoriev A, Stepantsov V. Countermeasures in longterm spaceflights. Russian experience. In: Proceedings of the 24th Annual Conference and the Annual Fall

Meeting of the Biomedical Engineering Society EMBS/BMES Conference. 2002. Oct 23-26: Houston (USA) 2002. p. 2162- 2163

34. Rathinam C, Spokes G, Bridges S et al. The effects of dynamic lycra body suit on a child with developmental coordination disorder - A single case study. *J Prosthet Orthot*. 25:58-61, 2010.

35. Sear J, Hoare T, Scanlan A et al. The Effects of Whole-Body Compression Garments on Prolonged High-Intensity Intermittent Exercise. *J Strength Cond Res* 24(7): 1901-1910, 2010.

36. Androjna C, McCabe N, Cavanagh P et al. Effects of Spaceflight and Skeletal Unloading on Bone Fracture Healing. *Clin Rev Bone Miner Metab* 10: 61-70, 2010.

37. Aagaard P. Training-induced changes in neural function. *Exerc Sport Sci Rev* 31: 61–67, 2003.

Table 1. Mean (±SEM) maximal ambulation angle (°) achieved in the GLCS and GYM clothing. * significant difference ($p<0.05$).

Condition	Shoulder Flexion (°)	Shoulder Extension (°)	Spinal Flexion at Yoke (°)	Spinal Extension at Yoke (°)	Spinal Flexion at T12 (°)	Spinal Extension at T12 (°)
GYM	183 ± 6	65 ± 4	143 ± 5	33 ± 3	82 ± 3	33 ± 3
GLCS	149 ± 8*	51 ± 9	105 ± 7*	21 ± 6*	56 ± 3*	11 ± 1*
	Hip Abduction (°)	**Hip Adduction (°)**	**Knee Flexion (°)**	**Knee Extension (°)**	**Sit and Reach (cm)**	**Get up and Go (s)**
GYM	60 ± 7	26 ± 3	113 ± 4	12 ± 1	27.7 ± 3.2	4.9 ± 0.1
GLCS	48 ± 6*	26 ± 5	100 ± 3*	11 ± 1*	14.9 ± 2.6*	5.6 ± 0.2*

Table 2. Mean (±SEM) number of final (3rd) set repetitions, average time to completion of sets (s) and delta core body temperature (ºC) in the GLCS and GYM clothing. * significant difference ($p<0.05$)

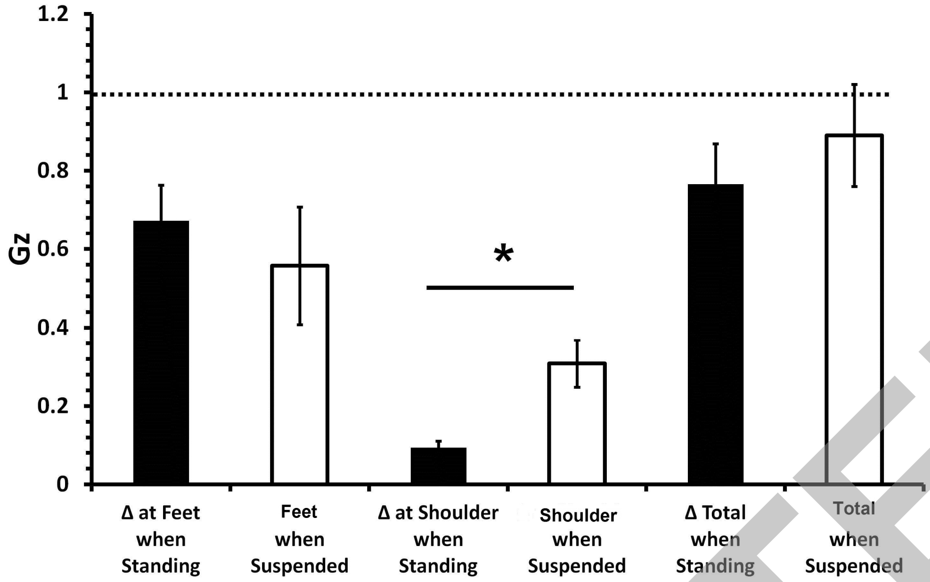
Number of Reps completed	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	12±0	12±0	12±0	12±0	12±0	12±0
GLCS	9±3*	12±0	12±0	12±0	12±0	12±0
Average time to completion (s)	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	30.4±4.9	30.1±7.8	24.1±6.4	24.1±6.4	29.3±6	21.3±6
GLCS	26.3±3.8*	27.5±8.1	26.5±9.1	23.2±8.3	30.9±9.5	18.5±5.2
∆ Temperature (°C) Pre – End of 3rd set	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	0.2±0.2	0.1±0.1	0.1±0.1	-0.1±0.1	0.1±0.2	0.1±0.1
GLCS	0.1±0.1*	0.1±0.2	0.1±0.1	0.1±0.1	0.1±0.1	0.1±0.1

Table 3. Median (interquartile range) Movement Discomfort and Body Control Ratings at the end of the final (3rd) set of strength exercise in the GLCS and GYM clothing. * significant difference ($p<0.05$).

Movement Discomfort	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	2 (2.0-2.0)	2 (2.0-2.0)	2 (2.0-2.3)	2 (2.0-2.0)	2 (2.0-2.3)	2 (2.0-2.0)
GLCS	8* (6.5-9.0)	7* (5.0-9.0)	6* (5.0-8.3)	5.5* (5.0-8.0)	5.5* (4.0-9.0)	5* (5.0-6.0)
Body Control	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	2 (2.0-2.0)	2 (2.0-2.3)	2 (2.0-2.3)	2 (2.0-2.0)	2 (2.0-2.0))	2 (2.0-2.0)
GLCS	7* (5.8-8.0)	6* (5.8-7.0)	5* (4.8-6.3)	5* (4.8-6.3)	5* (4.8-7.0)*	5* (4.8-6.0)

Table 4. Median (interquartile range) Rating of Perceived Exertion (RPE) and Thermal Comfort at the end of the final (3rd) set of resistance exercise in the GLCS and GYM clothing. * significant difference ($p<0.05$)

Rating of Perceived Exertion (RPE)	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	15 (13.8-15.8)	15 (13.8-15.5)	15 (14.8-15.8)	15 (14.8-16.0)	15 (14.8-16.3)	13.5 (13.0-14.3)
GLCS	16 * (15.0-19.0)	15.5 (13.8-17.3)	15 (14.0-15.5)	15 (14.0-15.5)	16 (15.5-19.0)	15 (13.8-15.0)
Thermal Comfort	**Shoulder Press**	**Squat**	**Chest Press**	**Seated Row**	**Leg Press**	**Calf Raise**
GYM	+2 (1.0-2.0)	+2 (1.8-2.0)	+2 (1.0-2.0)	+2 (1.8-2.0)	+2 (2.0-2.0)	+2 (1.0-2.0)
GLCS	+1 (0.8-1.3)	+2 (1.0-2.3)	+2 (2.0-3.0)	+1.5 (1.0-2.0)	+2 (2.0-3.0)	+1.5 (1.0-2.0)



1.2
1
0.8
0.6
0.4
0.2
0
Gz
*
Δ at Feet when Standing
Feet when Suspended
Δ at Shoulder when Standing
Shoulder when Suspended
Δ Total when Standing
Total when Suspended