Is a vibration isolation system required for Gateway? Mitigation of force and vibration transmission by the HIFIm jump sled during repeated jumping in microgravity

Daniel J Cleather
daniel.cleather@stmarys.ac.uk
St Mary's University

John E Kennett
Physical Mind London

Research Article

Keywords: VIS, exercise countermeasures, ISS, astronaut health, space exploration

Posted Date: April 25th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4251919/v1

License: ©  This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: Competing interest reported. J.E.K. is the inventor of HIFIm and has a financial interest in HIFIm through his ownership of the company Physical Mind London (PML). D.J.C. is currently on sabbatical with PML, however, he was not on sabbatical when the data presented here was collected and analyzed.
Abstract

Exercise countermeasures are a ubiquitous part of space habitation due to the need to mitigate the deconditioning effect of microgravity. However, exercise in space creates forces that need to be isolated from the habitat, and these so-called Vibration Isolation Systems (VIS) are typically large and heavy. High Frequency Impulse for Microgravity (HIFIm) is an exercise countermeasure that is designed to minimize force and vibration transmission to the spacecraft without the need for an additional VIS. The purpose of this study was to evaluate the effectiveness of HIFIm in mitigating force transmission in microgravity during parabolic flight. Force between HIFIm and the aircraft was measured using a custom-made arrangement of load cells during repeated jumping by two participants. Mean peak force transmission to the aircraft was $4.79 \pm 0.68 \text{ N.kg}^{-1}$. In addition, the frequency spectra for the upper and lower fixations to the aircraft were within the envelope of what is permissible for an exercise countermeasure on Gateway. These data support the design concept of HIFIm and suggest that HIFIm could be installed in a space habitat with no, or minimal, additional VIS. Measuring the force and vibration transmission of exercise countermeasures in microgravity during parabolic flight is highly challenging due to the safety constraints of the experimental platform and the extreme changes in acceleration (from 0-1.8g). The fact that this performance can be directly measured for HIFIm is a key advantage. The results presented here add to the mounting evidence that HIFIm is the future of exercise countermeasures.

INTRODUCTION

When astronauts spend time in microgravity they experience a significant loss of musculoskeletal health and cardiovascular fitness (Moore et al. 2014; Narici and de Boer 2011; Rittweger et al. 2018; Sibonga et al. 2015). The predominant reason for this is that the musculoskeletal systems of the astronauts are not loaded with the forces that they are accustomed to bearing on Earth. To mitigate this effect, astronauts spend a considerable chunk of the working day on countermeasure exercise. A key aspect of countermeasure exercise is to load the musculoskeletal system with forces that are similar to those experienced on Earth, and thus the production of high forces is desirable. At the same time, this therefore presents a challenge for the structural engineers who design and build spacecraft – how can these forces be isolated from the spacecraft such that they don't impair the structural integrity of the spacecraft?

The use of Vibration Isolation Systems (VIS) to mitigate the effects of countermeasure exercise on the spacecraft predates the International Space Station (ISS; Baugher and Ramachandran 1994). Each of three exercise devices that are currently employed on ISS have their own dedicated VIS (Korth 2015; McCrory et al. 1999; Moore et al. 2017; Niebuhr and Hagen 2011). The need for these systems greatly increases the space and mass requirements of each exercise countermeasure. For instance, the VIS underneath the T2 COLBERT treadmill is a cradle with a mass of 900kg (personal communication). Equally, a key challenge for some of the proposed future exercise countermeasures is the design and implementation of a VIS that can adequately mitigate force and vibration transmission to the spacecraft. For instance, the VIS that has been proposed to isolate the European Enhanced Exploration Device (E4D) has a mass approaching 400kg (Quiocho et al. 2023). The incorporation of large, heavy and expensive
VIS is clearly disadvantageous on space stations like ISS and Gateway (the planned space station that will orbit the moon) but might be impossible in deep space exploration missions where space and mass will be much more constrained.

High Frequency Impulse for Microgravity (HIFIm) is a custom-built horizontal jump sled which is designed to eliminate the need for a bulky VIS through an elegant application of Newton's laws. In particular, HIFIm is comprised of upper and lower carriages which are constrained to move equal and opposite to one another due to their mechanical connection by a rack and pinion system, with the resistance to movement provided by high tensile springs (Fig. 1). The user of HIFIm lies on the upper carriage, and mass can be added to the lower carriage such that the masses of the two carriages are equal. When the user of HIFIm jumps, there is an equal and opposite movement of two equal masses, and thus Newton's third law implies that the net force imposed by the whole HIFIm unit on the external environment should be zero. We have previously provided preliminary proof of concept of this design during the 77th European Space Agency (ESA) Parabolic Flight Campaign (PFC) in Bordeaux from 22nd to 28th October 2021 (Cleather et al. 2022) using the first prototype of HIFIm (HIFIm version 1). During that PFC, we showed that the force transmission from HIFIm to the aircraft was greatly reduced and almost negligible for most of the jump cycle. The main exception to this was an impact spike that was typically around 500N, and that occurred during the initial landing phase of the jump cycle.

Based on the data collected during our first PFC, and after consultation with national and commercial space agencies, we developed HIFIm version 2. A key aspect of the design was to refine the ability of HIFIm to mitigate force and vibration transmission to the aircraft. The purpose of this study was thus to extend the work that we performed in the first PFC and add to the data supporting HIFIm's engineering concept. We hypothesized that the force transmission to the aircraft would be lower than in our previous campaign with HIFIm version 1. In addition, we wanted to evaluate the impact of there being a small differential in the relative masses of the upper and lower carriages on the force transmission to the aircraft. We hypothesized that there would be an increase in force transmission if the masses of the upper and lower carriages were not perfectly matched, but that the effect would be modest.

**METHODS AND MATERIALS**

The data described here was obtained on 29th and 30th March 2023 in Bordeaux during the 64th Centre National D'Etudes Spatiales (CNES) PFC (VP171/64CNES).

**Participants**

Two participants performed repeated jumping in microgravity on HIFIm version 2. They were chosen to represent the widest range of possible body shapes and genders that might use an exercise countermeasure during spaceflight (Smith et al. 2020). To this end, participant 1 was a woman (age = 31 years, height = 165cm, weight 65kg) and participant 2 was a man (age = 33 years, height = 191cm, weight = 105kg). Both participants were highly practiced at jumping on HIFIm and had previous experience of
jumping on HIFIm in microgravity. Ethical approval for the study was provided by the institutional review board of St Mary's University, Twickenham (United Kingdom).

**Instrumentation**

HIFIm was instrumented with 4 load cells (Strainsense Load Beam Series LBS, Strainsense Ltd, Milton Keynes, UK) at the upper and lower ends of the sled (Fig. 2) to measure the forces between HIFIm and the aircraft. In addition, the movement of the upper carriage was captured with a single axis accelerometer (Model 4000A Accelerometer, Strainsense Ltd, Milton Keynes, UK). All instrumentation was wired into a NI 9205 voltage input module and captured synchronously through a NI cDAQ 9171 data logger (both from National Instruments Corp, 11500 North Mopac Expressway, Austin, TX 78759 – 3504, USA). A bespoke LabView NXG 5.0 (also National Instruments) script was written to process, display and save the data in real time.

**Procedure**

Data were collected during 2 parabolic flights consisting of 31 parabolas each. The first parabola of each flight was used for familiarization and no jumps were performed. Following that, participant 1 jumped during the next 15 parabolas, and then participant 2 jumped for the final 15 parabolas. During each parabola, the load cell instrumentation was monitored in order to establish when microgravity had been achieved. Once the weight of HIFIm was registered as zero, participants were instructed to start jumping, with a target of completing 10 jumps. The first and last jumps from each set were not included in the analysis due to their different profile in comparison with repeated jumping. In total, the data presented here consists of jumps from 28 parabolas for each participant (participant 1: 213 jumps; participant 2: 222 jumps). Each participant wore an adjustable weight vest with pockets that could accept small weights of 0.063kg. The mass of the participant could thus be adjusted between parabolas, thereby effectively changing the mass differential between the two carriages. Jumping was performed with the carriages perfectly balanced, with the upper carriage having greater mass, and with the lower carriage having greater mass. The range of mass differentials tested can be seen in Fig. 3. Participant 1 jumped against a resistance of 2 springs whereas participant 2 had a resistance of 4 springs.

**Data and Statistical Analysis**

Numerical analysis was performed using GNU Octave ([www.gnu.org](http://www.gnu.org)) and Microsoft Excel. The acceleration data (of the upper carriage) was filtered using a 5th order Butterworth low-pass filter at 10 Hz. The filtered data was then used to identify the start and end of each jump cycle – beginning and ending at the initial contact with the force plate during landing. All data for each jump cycle was time normalized to an epoch of 1 unit and spline interpolated into intervals of 0.01 unit. This permitted the calculation of the mean and standard deviation at each time point for both the acceleration and force data across all jumps, and across the subset of jumps when the upper and lower carriages of HIFIm were balanced. In addition, for each parabola, the mean peak force was calculated, and the Pearson correlation
between the mass differential and the mean peak force calculated. Finally, the frequency spectrum of force transmission was calculated using Fourier analysis using the `fft()` function in GNU Octave.

RESULTS

Relative to the body mass of the participant, the mean peak force transmission to the aircraft was $4.79 \pm 0.68 \text{ N.kg}^{-1}$ (Fig. 3). Peak force transmission was measured in the load cells at the lower end of HIFIm immediately upon landing (Fig. 4). Peak force transmission from the load cells at the upper end of HIFIm was measured at peak extension of HIFIm. The best case scenario was considered to be during jumping by the 65kg woman with the upper and lower carriages of HIFIm optimally balanced (Fig. 4; mean peak force transmission: lower carriage – $186.0 \pm 78.4 \text{ N}$; upper carriage – $165.1 \pm 29.4 \text{ N}$). The worst case scenario was considered to be during jumping by the 105kg man with a range of mass differentials between the upper and lower carriages of HIFIm (mean peak force transmission: lower carriage – $389.7 \pm 150.8 \text{ N}$; upper carriage – $350.6 \pm 31.5 \text{ N}$).

There was a weak parabolic relationship between the effective mass differential between the two carriages and the mean peak force transmission when the data from both participants was analyzed together ($R^2 = 0.23$; Fig. 4). When this data was analyzed separately, there was a parabolic relationship for the 65 kg woman ($R^2 = 0.50$) but no relationship for the 105 kg man ($R^2 = 0.05$).

Force transmission at the upper end of HIFIm was principally seen at low frequencies (0–2 Hz; Fig. 5). The frequency spectrum was a little wider for the load cells at the lower end of HIFIm, but force transmission was below 25N for frequencies above 5Hz.

DISCUSSION

The principal finding of this study was that when the upper and lower carriages of HIFIm were perfectly balanced, the mean peak force transmission to the aircraft was around $4.5 \text{ N.kg}^{-1}$. Based on the anthropometric characteristics of previous astronauts (Rajulu and Klute 1993), and the likely anthropometry of astronauts on future missions (Scott et al. 2023; Scott et al. 2020), this suggests that the peak force transmission of the ‘typical’ astronaut in a future mission will be $330 \pm 45 \text{ N}$. We hypothesized that the peak force transmission when using HIFIm version 2 would be lower than for HIFIm version 1. Participant 1 in this study also took part in our previous campaign using HIFIm version 1. During that PFC their mean peak force transmission was around 340N when jumping against a resistance of 2 springs, over 500N when jumping with 3 springs and around 360 N when using 4 springs (Cleather et al. 2022). In the current study, the same participant produced a total mean peak force transmission of around 175 N against a resistance of 2 springs. This provides robust support for our hypothesis that HIFIm version 2 performs better in terms of force transmission than version 1 – the force transmission was approximately half that seen with version 1.
Our secondary hypothesis was that the force transmission to the aircraft would be sensitive to the mass differential between the two carriages. This hypothesis follows from Newton’s Laws, that is, if the masses of the carriages are not equal then the net external force will not be equal. Confirmation of this hypothesis would also serve as an implicit validation of the engineering concept. For participant 1, there was a parabolic relationship between the mass differential of the carriages and the force transmission – 50% of the variability in the mean peak force transmission between parabolas could be explained by the mass differential between the carriages. However, for participant 2 no relationship was seen. There are two possible explanations for this. The first is that participant 1 was a much more experienced user of HIFIm and had also operated HIFIm in microgravity in our previous campaign. It is likely that her jumping pattern was more repeatable, with less variability, thus making the relationship easier to detect. The second potential explanation is that participant 2 was 40 kg heavier than participant 1. This means that unbalancing of the carriages was less relative to body weight for participant 2. In any case, this study demonstrates that, as would be expected from the fundamental principles of classical mechanics, HIFIm is sensitive to the mass differential between the carriages. However, a small differential between the two carriages is likely not critical, as in this study, a differential of ±1 kg resulted in a negligible difference in force transmission.

NASA and ESA have begun to release information as to the parameters that any exercise countermeasure for Gateway will need to meet. We have been given confidential access to the envelope of forces relative to frequency that will be acceptable for Gateway. The frequency spectrum of the force transmission to the aircraft presented in Fig. 5 is designed to address this parameter. We believe that the force and vibration transmission seen here is within the acceptable envelope for Gateway for both the fixation under the upper and lower ends of HIFIm. What is important to note here is that the acceptable envelope that we have seen relates to the force and vibration transmission after mitigation by a VIS. In contrast, the spectrum seen in Fig. 5 relates to the forces transmitted to the aircraft directly from HIFIm, without any additional VIS. To put this another way, HIFIm is its own VIS, as the equal and opposite movement of the two equal masses nullifies the expression of external forces.

When considering the force transmission to the aircraft, there are some important limitations due to the nature of parabolic flight. In particular, any hardware taken on the plane needs to meet the safety criteria of the parabolic flight operator (Novespace). One key criterion is that mechanical structures should be sufficiently robust to resist the forces to which they might be exposed in the event of an emergency landing. This requirement is very limiting in terms of maximizing the vibration and force isolation performance of HIFIm as the fixation of HIFIm to the aircraft needs to be firm and very strong. For instance, the connection between HIFIm and the aircraft is via wire loops (these can be seen in Fig. 2, immediately above the load cells). Due to the Novespace requirements these are of very heavy gauge, and in microgravity provide little shock absorbing effect. However, in any version of HIFIm that was configured for operation in space we could use a much less rigid attachment that would likely confer a significant additional reduction in force and vibration transmission. The vibration and force transmission results reported here should therefore be taken as a highly conservative upper bound on what would be
achievable in space – the force and vibration transmission of a spaceflight version of HIFIm would likely be much lower.

It is also interesting to observe that the challenges of testing an exercise countermeasure in parabolic flight have prevented many devices from being evaluated on this platform. For instance, the development of the VIS for E4D has been pursued through modelling and laboratory testing – the performance of the VIS has not been quantified in parabolic flight, nor will it be (personal communication; Quirocho et al. 2023). The same is true for the Advanced Resistive Exercise Device (ARED) currently used on ISS, and its predecessor the Interim Resistive Exercise Device (iRED; Niebuhr and Hagen 2011). In fact, the actual (local) vibration and force isolation performance of ARED has not even been tested on ISS – the effectiveness of ARED’s VIS has only been evaluated by looking at the overall acceleration of ISS as measured by the onboard accelerometers (Niebuhr and Hagen 2011). The data presented here is thus highly unusual, and as far as we are aware, may be unique. Certainly, the ability to measure the actual vibration and force isolation of the device, rather than relying on modelling and simulations, is a huge advantage supporting the use of HIFIm in future space habitats.

This study focused on repeated horizontal jumping. Jumping results in the production of large impact forces that are not seen in less ballistic exercises, which, as discussed in the introduction, is an advantage in terms of the efficacy of a countermeasure exercise. However, the presence of these impact spikes likely makes the isolation of force and vibration more challenging. We contend here that HIFIm can reduce force and vibration transmission to levels such that an additional VIS is not required, even during the most demanding of exercise modes. The performance of HIFIm in the present study thus needs to be understood in this context. To our knowledge, repeated jumping has never been performed in space, thus this paper provides proof of concept of HIFIm’s engineering design during activity that exceed current operational practice.

Although this study only considers jumping, it is important to emphasize that HIFIm is a multi-modal piece of exercise equipment with a menu of over 100 potential exercises. Using HIFIm, it is possible to perform versions of all the current exercises performed on ARED (Petersen et al. 2016) and many more. Again, the force and vibration transmission seen in this study serves as a conservative upper bound for what might be expected when performing these exercises on HIFIm, and the actual force and vibration transmission will likely be much lower. There is no necessity to use HIFIm for repeated jumping, it is a highly effective countermeasure when used for the more traditional style of resistance exercise that is currently employed on ISS. Thus, even if the repeated jumping was considered to produce impact forces that were unacceptable for a space habitat like Gateway, HIFIm would still be a compelling choice as a countermeasure, as it provides a complete menu of exercise options without the need for an additional VIS.

In summary, in this study we have shown that force and vibration transmission to the aircraft is minimal during repeated jumping on HIFIm, and possibly within the envelope of what is acceptable for Gateway, without the use of an additional VIS. As future spaceflight ready versions of HIFIm will be further
optimized to reduce force transmission, this paper provides compelling evidence that HIFIm can be implemented in future space habitats with minimal or no additional VIS. HIFIm is already a compact and relatively light piece of exercise equipment. The lack of necessity for a bulky and heavy VIS adds to the compelling evidence that is mounting, supporting HIFIm as the future of exercise countermeasures.

**Declarations**

**Acknowledgements**

The authors would like to thank Becky Owen, Sam Callaghan, Alexandra Jaquemet, Phil Price, Jazmin Morrone, Jon Scott and Dave Green.

**Author Contributions**

D.J.C. was the Principal Investigator. The methods were designed by, and data were collected by D.J.C. and J.E.K. Data analyses were performed by D.J.C. D.J.C. wrote the first draft of the manuscript – both authors agree to the final version of the manuscript.

**Ethics approval**

Ethics approval was awarded by the St Mary’s University ethics board.

**Funding**

This project was funded by the UK Space Agency (grants: ST/X002004/1). Access to the experimental platform (a PFC) was provided by the European Astronaut Centre (EAC) of ESA.

**Conflict of interest**

J.E.K. is the inventor of HIFIm and has a financial interest in HIFIm through his ownership of the company Physical Mind London (PML). D.J.C. is currently on sabbatical with PML, however, he was not on sabbatical when the data presented here was collected and analyzed.

**Availability of data and material**

The data described in this study is commercially sensitive. It can be provided to relevant parties who are not commercial competitors under the terms of a non-disclosure agreement on reasonable request to the corresponding author.

**Consent to participate.**

Written consent was obtained from each participant in this study.

**Consent for publication**
I have read and understood the publishing policy and submit this manuscript in accordance with this policy.

References


   https://doi.org/10.1007/s12217-022-09987-8


   https://doi.org/10.1152/japplphysiol.01251.2013@apsselect.2014.1.issue-9


Figures
Figure 1

High Frequency Impulse for Microgravity (HIFIm) version 2 schematic diagrams. A) HIFIm in closed position. B) HIFIm at full extension – the upper and lower carriages have moved equal and opposite to one another. The middle carriage contains the attachment points to the aircraft and has not moved. C&D) Expanded diagrams of HIFIm showing component parts.
Figure 2

Position of load cells with HIFIm in situ for jump testing in microgravity during the 64th CNES parabolic flight campaign (VP171/64CNES) in Bordeaux.
Mean peak force transmission from HIIFm to the aircraft during repeated jumping in the microgravity phase of parabolic flight by a 65kg woman and a 105kg man. Each data point represents a set of jumps performed during one parabola. Error bars represent the 95% confidence interval. Data was recorded during the 64th CNES parabolic flight campaign on 29th and 30th March 2023.
Figure 4

Mean force transmission from HIFIm to the aircraft during repeated jumping in the microgravity phase of parabolic flight. Force was recorded from load cells at the lower (solid black line) and upper (dotted black line) ends of HIFIm (the grey line is the horizontal acceleration of the upper carriage and the fine dotted black lines represent the 95% confidence intervals). The best case scenario is jumping by a 65kg woman with resistance of 2 springs and optimal mass differential between the upper and lower carriages (70 jumps recorded over 9 parabolas). The worst case scenario is for jumping by a 105kg man with a resistance of 4 springs and a range of optimal and non-optimal mass differentials between the upper and lower carriages (222 jumps recorded over 28 parabolas). Data was recorded during the 64th CNES parabolic flight campaign on 29th and 30th March 2023.
Figure 5

Frequency spectrum of force transmission from HIFIm to the aircraft during repeated jumping in the microgravity phase of parabolic flight by a 65kg woman (black lines) and 105kg man (grey lines). Force was recorded from load cells under the upper and lower carriages. Dotted lines represent the 95% confidence interval. Data was recorded during the 64th CNES parabolic flight campaign on 29th and 30th March 2023.