TITLE
Repeated horizontal jumping is a feasible exercise countermeasure for microgravity

AUTHOR
Cleather, Daniel J.; Price, Phil D. B.; Kennett, John E.

JOURNAL
Microgravity Science and Technology

DATE DEPOSITED
24 November 2022

This version available at
https://research.stmarys.ac.uk/id/eprint/5549/

Cleather, D.J., Price, P.D.B. & Kennett, J.E. Repeated Horizontal Jumping is a Feasible Exercise Countermeasure for Microgravity. *Microgravity Sci. Technol.* **34,** 68 (2022). https://doi.org/10.1007/s12217-022-09987-8

Repeated horizontal jumping is a feasible exercise countermeasure for microgravity

Daniel J Cleather[1,2*], Phil DB Price[1] and John E Kennett[3]

[1] St Mary's University, Waldegrave Road, Twickenham, TW1 4SX, UK
[2] Institute for Globally Distributed Open Research and Education (IGDORE)
3 Physical Mind London, Teddington, TW11 8HH, UK

* Corresponding author: daniel.cleather@stmarys.ac.uk; +420 775 255 586

Keywords: jump sled; amputee; para-astronaut; space exploration; HIFIm

Word count: 2900

Figures: 6

Tables: 1

24/11/2022

ABSTRACT

Objectives: Astronauts who spend prolonged time in microgravity on the International Space Station can experience a significant reduction in physical fitness. Jumping exercises represent a potential solution to this problem as the European Space Agency has demonstrated that the deconditioning effect of long-term bed-rest can be countered with around four minutes per day of jumping. The purpose of this study was to evaluate if repeated jumping is possible in microgravity and if the transmission of impact forces and vibration to the aircraft can be minimised.

Methods: Five subjects performed repeated jumping on a custom jump sled both in microgravity during a parabolic flight campaign and in normal gravitational conditions. Forces expressed by the user and transmitted to the aircraft were quantified using a bespoke instrumentation system.

Results: These results show, for the first time, that repeated horizontal jumping is possible in microgravity, and that force transmission can be minimised by using a custom supine jump sled. The peak effective ground reaction force experienced by the user was sensitive to both the style of jumping used and resistance employed.

Conclusion: These results open the door to the next generation of exercise countermeasures for deep space exploration. In particular, we have qualified the High Frequency Impulse for Microgravity (HIFIm) exercise device to a Technology Readiness Level of 6 making it a leading candidate to replace the Advanced Resistive Exercise Device (ARED) which has been in service since 2009.

INTRODUCTION

A key challenge to the success of space exploration missions is the fact that humans experience significant deconditioning when spending a prolonged period of time in microgravity [1]. These effects are wide ranging and include a loss of bone mineral density (BMD), muscle strength, aerobic fitness and musculoskeletal function [2–4]. For this reason, astronauts spend a considerable amount of time on ‘countermeasure exercise’ that is designed to mitigate these decrements in physical fitness. In particular, up to 25% of the working day on the International Space Station (ISS) is spent on exercise countermeasures [5]. Despite this, it is still common that astronauts returning from ISS after long duration missions exhibit substantial deconditioning.

Recently, interest in the use of jumping as an exercise countermeasure has increased. This is predominantly driven by the success of a European Space Agency (ESA) study that demonstrated that the deconditioning effect of long-term bed-rest could be mitigated with just 3-4 minutes of repeated jumping activity daily using a horizontal ‘jump sled’ that provides a resistance that returns the user to the take-off surface after each jump [6–8]. Jumping is thought to be effective because it is a form of impact exercise that requires high levels of muscular activation [9]. In addition, the resistive element of training on the jump sled apparatus is also beneficial in preserving bone density [10,11] and muscle strength [12,13], making this form of exercise highly effective.

Jumping could therefore be a potent strategy to increase the effectiveness of countermeasure training while reducing its time demands. Of course, there is clearly a technical challenge to be overcome in order to jump repeatedly in the absence of gravity. One solution to this is the use of the aforementioned jump sleds which provide a resistance to movement that compensates for the lack of gravity and that return the user to the ‘ground’ (or jump board) after each jump.

Such a jump sled was employed in the ESA bed-rest study [6,14]. However, it has yet to be demonstrated if such jump sleds actually work in microgravity and whether repeated jumping is feasible. A second major challenge to the realisation of repeated jumping as an exercise countermeasure is the need to ensure that the impact forces and vibration created during exercise are not transmitted to the spacecraft. This is important both from a safety perspective but also because space habitats like ISS are laboratories with experiments that are sensitive to external forces.

The High Frequency Impulse for Microgravity (HIFIm) jump sled has been designed to address the unique challenges of jumping in microgravity. In particular, the sled is comprised of upper and lower carriages of equal mass, that move equal and opposite to one another during jumping, and which should minimise force transmission. The purpose of this study was thus to evaluate whether HIFIm could be used to facilitate repeated jumping in microgravity during parabolic flight. The study had two aims. The first was to establish the feasibility of jumping in microgravity using HIFIm. The second was to test the hypothesis that the design of HIFIm would minimise force transmission to the aircraft.

MATERIALS AND METHODS

This experiment was a feasibility study to evaluate whether HIFIm can be used to facilitate repeated horizontal jumping in microgravity. Testing was performed from 22nd to 28th October 2021, during the 77th European Space Agency Parabolic Flight Campaign in Bordeaux. Five subjects performed repeated jumping exercise on HIFIm in both microgravity and normal gravitational conditions.

Subjects

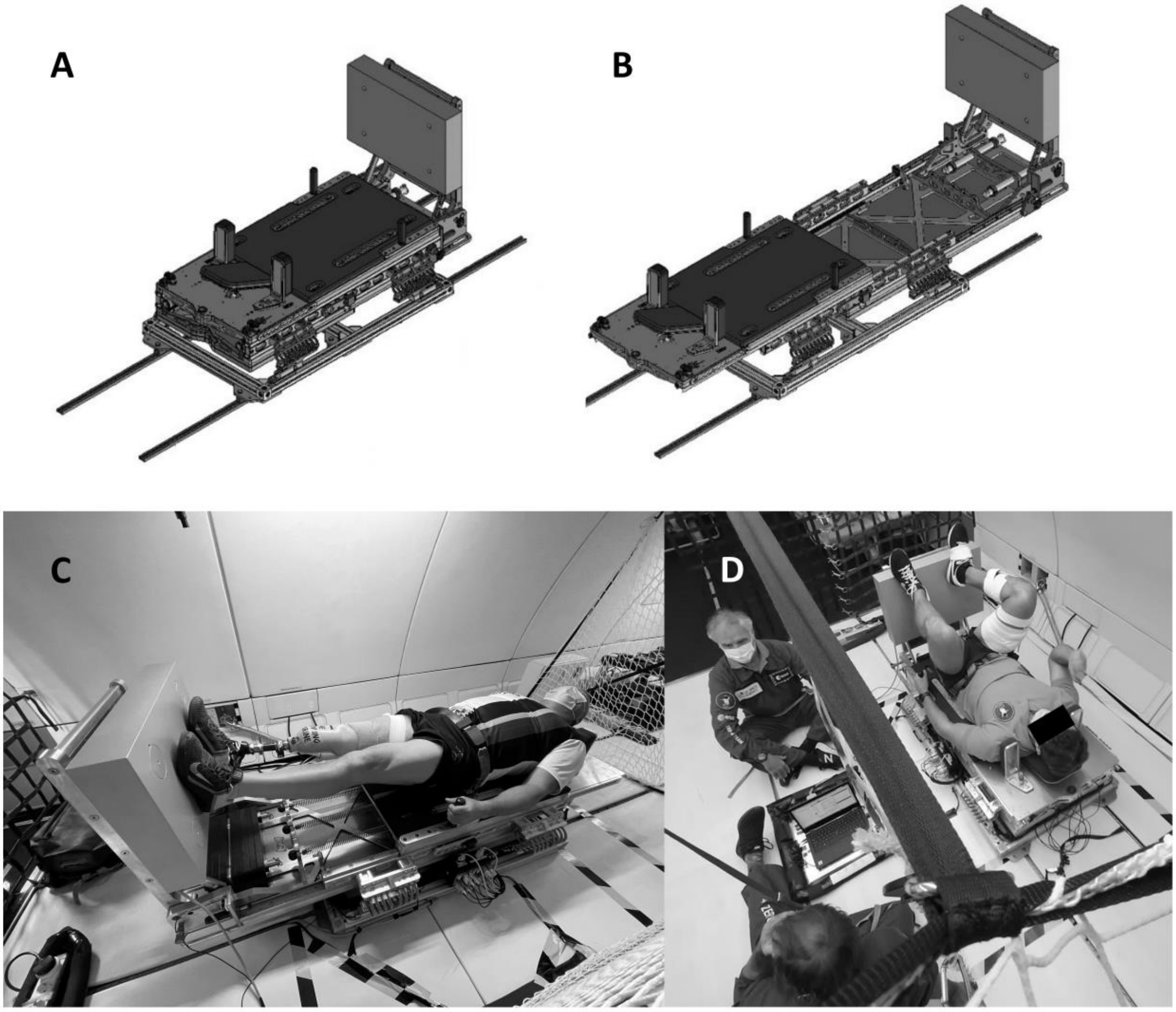
The subjects recruited for this study were prospectively chosen to ensure a range of body sizes and sexes that are reflective of potential users (i.e. astronauts; Table 1). All subjects had previous experience of jumping on HIFIm prior to the study and took part in further familiarisation practice prior to data collection. Ethical approval for this study was provided by St Mary's University, Twickenham, United Kingdom and the Comité de Protection des Personnes Nord-Ouest II, Amiens, France (21.01095.000005). The study was conducted in accordance with the Declaration of Helsinki (seventh revision) and all subjects provided informed written consent prior to experimentation.

Table 1. Subject characteristics.

Subject	Sex	Age (years)	Height (m)	Mass (kg)	Spring Resistance (No. of Springs)		
					Set 1	Set 2	Set 3
1	F	35	1.62	56	3	4	2
2	M	52	1.80	94	2	3	2
3	M	51	1.70	84	3	4	2
4	F	30	1.65	63	4	5	3
5	M	35	1.87	91	4	5	3

Instrumentation

High Frequency Impulse for Microgravity (HIFIm; Figure 1) is a prototype system designed to facilitate a range of exercise countermeasures in microgravity. HIFIm is sled-based and comprised of upper and lower moving carriages that are mechanically connected via a rack and pinion such that the movement of the carriages is constrained to be equal and opposite (Figure 1). Resistance to movement is provided by high tensile springs that link the upper and lower carriages. The mass of the user is borne by the upper carriage and the mass of the lower carriage is equalized to the mass of the upper carriage system by the addition of balance weights. The user jumps by pushing against the force plate that is mounted on the jump plate of the lower carriage.



[redacted]

Figure 1. HIFIm. A) closed position; B) open position; C) side view during 1g testing; D) view from above during microgravity testing.

A bespoke instrumentation system was developed to capture the forces expressed during the operation of HIFIm and the muscular activity of the user. This included a Kistler

Multicomponent Force Plate (Type 9281E; Kistler Group, Eulachstrasse 22, 8408 Winterthur, Switzerland), 4 load cells (Strainsense Load Beam Series LBS; Strainsense Ltd, Old Strafford Business Park, Falcon Drive, Old Stratford, Milton Keynes, MK19 6FG, United Kingdom) to measure the force between HIFIm and the aircraft and 3 wireless electromyography (EMG) sensors (Cometa Wave Plus; Cometa srl, Via Verdi 24, 20080 Cisliano MI, Italy). All of the data collection equipment was wired into a single National Instruments data logger (NI cDAQ 9171 with a NI 9205 voltage input module; National Instruments Corp, 11500 North Mopac Expressway, Austin, TX 78759-3504, USA) to ensure the synchronous collection of data. A custom LabView NXG 5.0 (also National Instruments Corp) script was developed to manage the instrumentation and to display and record all data. Data was collected at 1000 Hz. The EMG signals were processed in real-time in LabView every 0.1s. The signal was first filtered using a 2nd order, Butterworth band pass filter (10 – 500 Hz), rectified, and then passed through a 2nd order, Butterworth low pass filter (10 Hz) to obtain the linear envelope.

Procedure

Prior to each flight, each subject was equipped with EMG electrodes on the right leg, following SENIAM guidelines (http://www.seniam.org/). Firstly, the skin was prepared by shaving and then cleaning with an alcohol wipe. Electrodes were then placed on the gluteus maximus (halfway between the sacral vertebrae and the greater trochanter), vastus lateralis (two thirds of the way from the anterior spina iliaca superior to the lateral side of the pelvis) and on the most prominent bulge of the medial gastrocnemius. Maximum voluntary contractions (MVCs) were then performed against the manual resistance of a member of the research team.

Each parabolic flight comprised 31 parabolas. The first parabola was used to take baseline readings from HIFIm with the user remaining still and not in contact with the force plate. Following this, parabolas were performed in sets of 5, with a new parabola starting every 3 minutes. There was a 5 minute break between each set of 5 parabolas and a break of 8 minutes after the first 15 parabolas. The microgravity phase of each parabola was of approximately 22 seconds duration. The campaign consisted of 3 flights. Each subject exercised on HIFIm for 15 parabolas and so 2 subjects were tested on each flight except for the final flight where only 1 subject was tested. The 8 minute break after 15 parabolas was used for the change-over of subjects and the 5 minute breaks between sets of 5 parabolas were used to change the spring resistance.

A moderate spring resistance was used for the first set of parabolas which was used to accustom the user to jumping in microgravity (Table 1). The appropriate spring resistance was determined during familiarisation based upon the clinical judgment of the inventor of HIFIm (JEK). During the first parabola the user simply squatted in order to get used to moving on HIFIm in microgravity. The next 2 parabolas were used to practise normal bilateral jumping, with the user instructed to take their time getting used to the environment. By the fourth parabola all subjects were comfortable moving on HIFIm and were able to jump normally – generally subjects were asked to complete 10 jumps within the microgravity phase of a parabola. The spring resistance was increased for the second set of 5 parabolas. Finally, the spring resistance was decreased for the third set which was used to experiment with different jumping styles. In this final set, subjects performed 1 set of bilateral jumping, 2 sets of bilateral rebound jumps (i.e. jumping with a stiffer landing, involving less knee flexion and more emphasis on using the ankle as the means of propulsion) and 2 sets of unilateral jumps using the right leg.

An audio recording that replicated the cabin announcements made during the flight was created to simulate the timings of the parabolic flight. Each subject took part in a simulated parabolic flight on the ground prior to taking part in an actual flight. This ground-based testing was performed within the plane using all of the protocols described above.

Statistical Analysis

The fourth, fifth and sixth jumps from each parabola were chosen for analysis to ensure that the analysed jumps were performed in microgravity after the user had established their jumping rhythm. Jumps were chosen such that there were representative jumps for each spring resistance and jump style. The start of each jump was identified as being the frame when the user first made contact with the force plate and ended at the frame that preceded the next contact with the first plate. Each jump was time normalised to a nominal time period of 1 unit, and then spline interpolated in GNU Octave (www.gnu.org) to find values of the variables of interest (effective ground reaction force from the force plate, eGRF; force between HIFIm and the aircraft measured from the load cells; EMG activations normalised to MVCs) at regular intervals of 0.01 unit [15,16]. The mean and standard deviations at each time point were taken to produce composite representative time series and 95% confidence intervals for each jump condition and variable of interest. In particular, we present representative curves for set 1 (lighter spring resistance), set 2 (heavier spring resistance) and for the three different jump styles used in set 3. A multivariate repeated measures analysis of variance performed in IBM SPSS Statistics (version 26; IBM, Armonk, NY) was used to test for differences in peak muscular activations between gravitational conditions and set number.

RESULTS

All subjects used HIFIm without difficulty in microgravity and generally reported that jumping in microgravity felt similar to normal gravity. There was a high degree of similarity between the force-time profiles of repeated jumping in microgravity and normal gravity (Figure 2). The exception to this is for the male amputee in 1g, who despite his familiarity with HIFIm, was very cautious when first jumping on HIFIm within the experimental environment (i.e. with HIFIm actually loaded onto the aeroplane). Mean peak eGRFs ranged between 600 and 1000N. Mean peak eGRFs were higher when the spring resistance was greater (i.e. in set 2 compared to set 1). The relative length of the flight phase of the jump was greater when spring resistance was lower. The forces between HIFIm and the aircraft were greatly reduced in microgravity and were negligible for much of the jump cycle (Figure 3). The peak force was subsequent to the participant first making impact with the force plate, and in microgravity was typically around 500N.

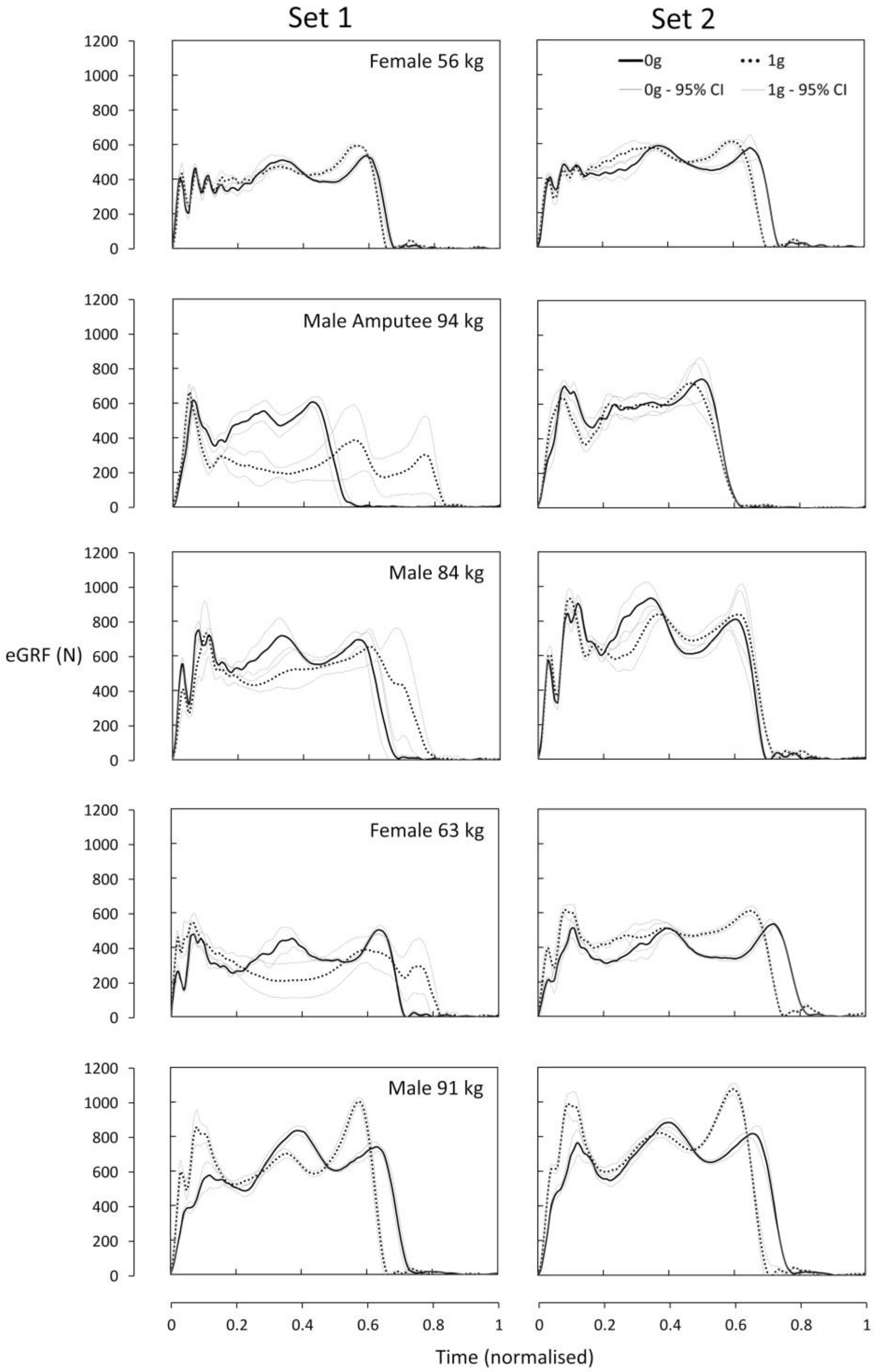


Figure 2. Mean effective ground reaction forces (eGRF) expressed during repeated horizontal jumping on HIFIm in normal (1g) and microgravity (0g). Mean is taken over a number of single jump cycles. Set 1 jumps are performed against a lighter resistance than set 2 (CI = confidence interval).

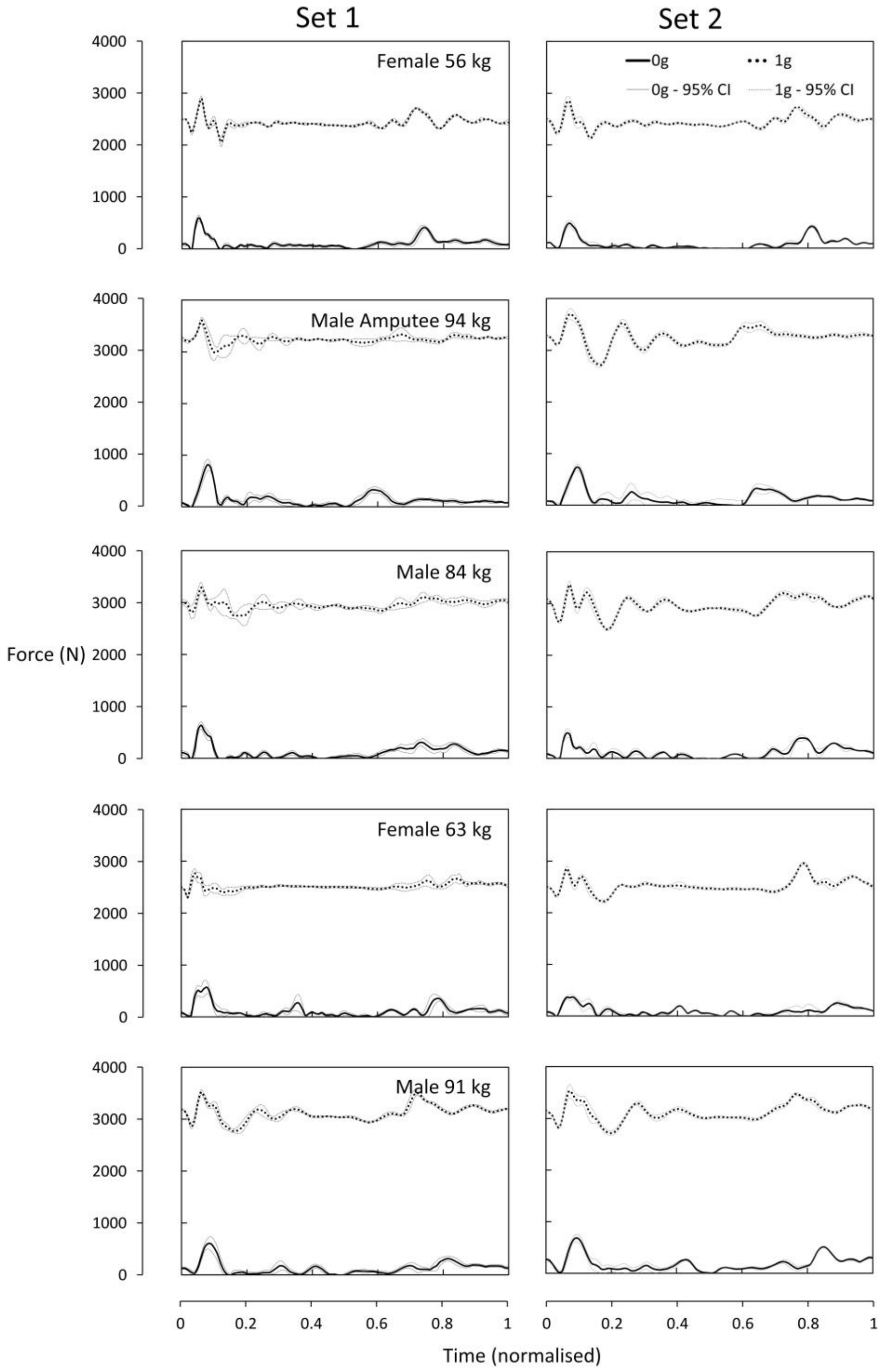
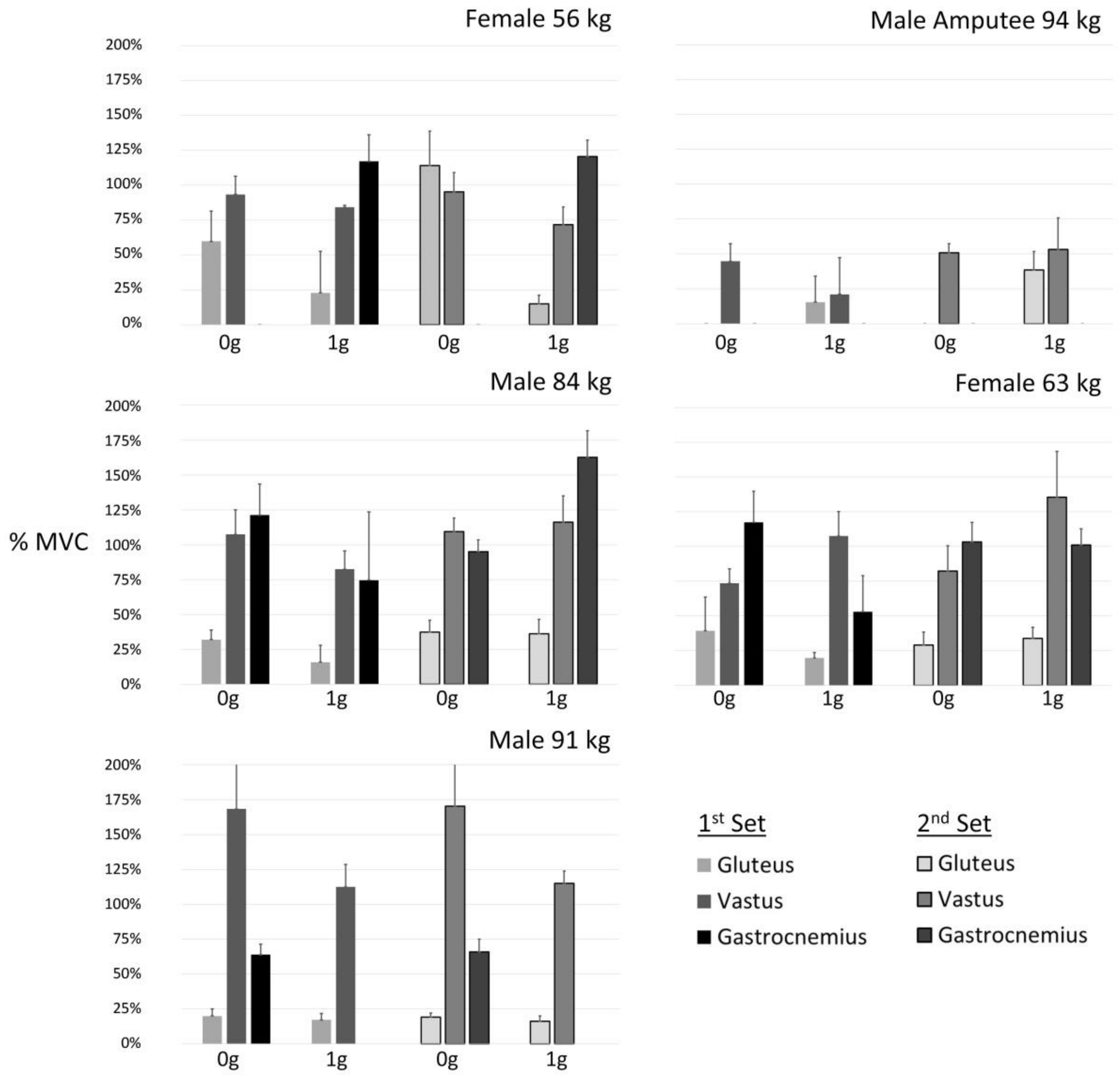


Figure 3. Mean forces between HIFIm and aircraft during repeated horizontal jumping on HIFIm in normal (1g) and microgravity (0g). Mean is taken over a number of single jump cycles. Set 1 jumps are performed against a lighter resistance than set 2 (CI = confidence interval).

Muscular activation of the lower limb was substantial during jumping on HIFIm in both microgravity and normal gravity (Figure 4). There were no statistically significant differences between the muscular activations seen in microgravity or normal gravity or between set 1 and set 2. There was considerable variation in the peak muscular activities but some broad trends were observed. In particular, mean peak activity of the vastus and gastrocnemius was typically at, or in excess of, 100% of the MVC value. Conversely, mean peak activity of the glutes was typically between 25% and 50% of MVC.



218

219 Figure 4. Mean peak muscular activity as a percentage of maximal voluntary contraction 220 (MVC) during repeated horizontal jumping on HIFIm in normal (1g) and microgravity (0g). 221 Mean is taken over a number of single jump cycles. Set 1 jumps are performed against a lighter 222 resistance than set 2. Error bars indicate the 95% confidence interval. Missing data is due to 223 equipment failure during data collection.

224

225 The mean peak eGRFs were very sensitive to the jumping style employed. In particular, the 226 stiffest jump style (bilateral rebounding) produced the greatest mean peak eGRFs of between

1000 and 1200N (Figure 5). This was significantly greater than the mean peak eGRFs of 300 to 800N during bilateral ‘normal’ jumping that were seen at the same spring tension. In addition, the force-time curves for unilateral jumping were notably similar to those seen during bilateral jumping. There was a weaker relationship between jumping style and mean peak force between HIFIm and the aircraft (Figure 6). For 3 of the 4 subjects, unilateral jumping produced the lowest mean peak forces whereas rebound jumping produced the highest forces.

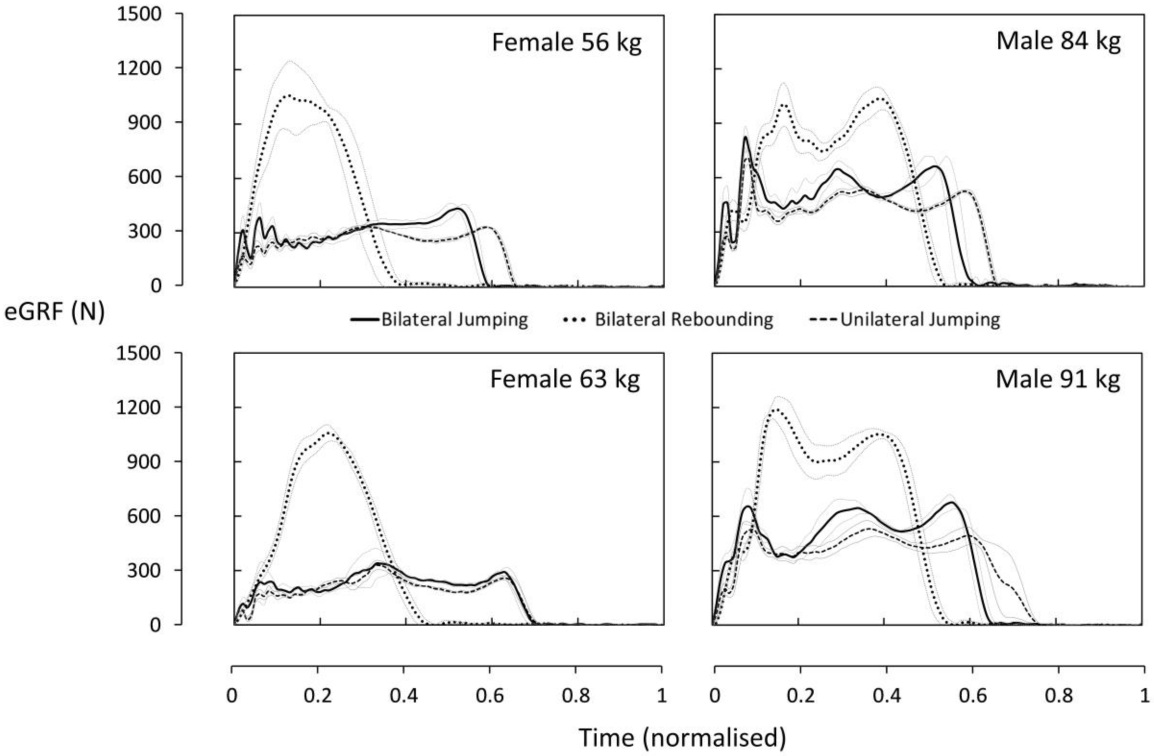


Figure 5. Mean effective ground reaction forces (eGRF) expressed during repeated horizontal jumping on HIFIm in microgravity for 3 different styles of jumping. Mean is taken over a number of single jump cycles. Lighter lines indicate the 95% confidence interval.

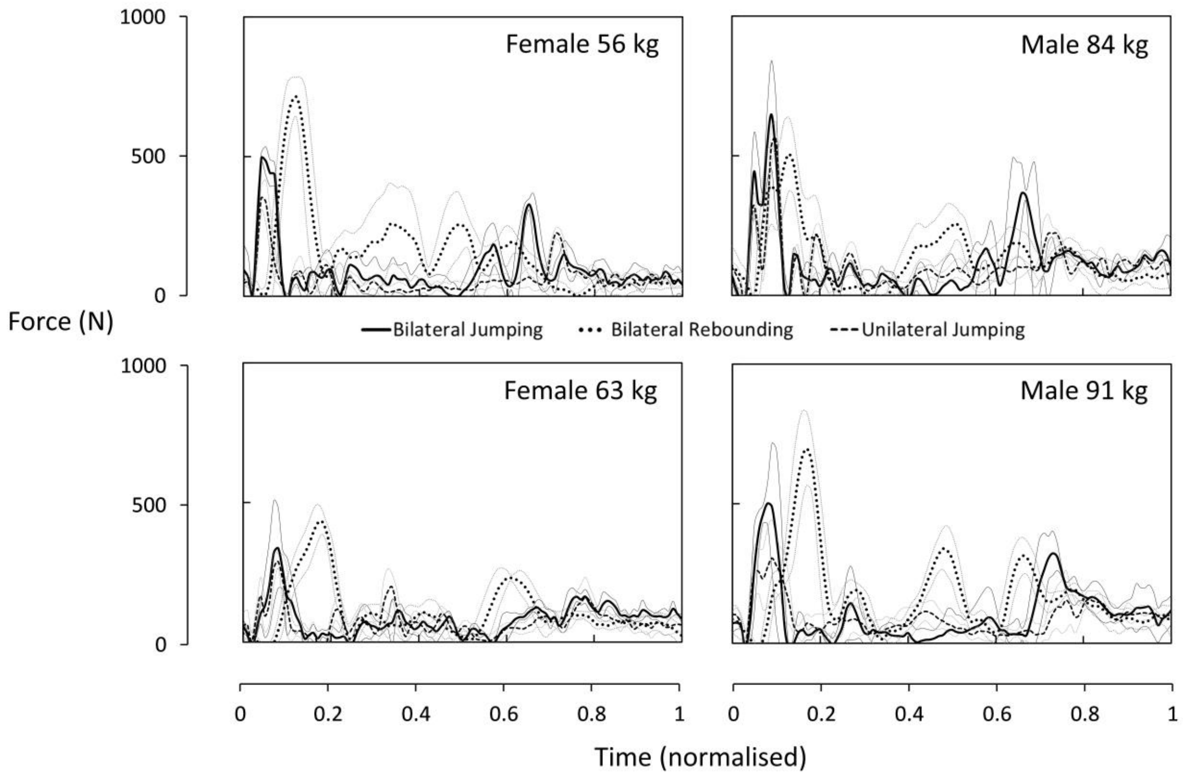


Figure 6. Mean forces between HIFIm and aircraft during repeated horizontal jumping on HIFIm in microgravity for 3 different styles of jumping. Mean is taken over a number of single jump cycles. Lighter lines indicate the 95% confidence interval.

DISCUSSION

The purpose of this study was to evaluate the feasibility of performing repeated jumping in microgravity using HIFIm. We found that subjects were quickly able to master the skill of jumping in microgravity and reported that the experience of jumping in microgravity was not notably different from jumping in normal gravity. This study therefore demonstrates, for the first time, that repeated jumping using a horizontal jump sled is a realistic possibility as a future exercise countermeasure. In addition, the subjects who took part in this study represented a diverse range of users, which suggests that HIFIm potentially has wide utility. Notably, one of the subjects in this study was a lower limb amputee, who was also able to exercise effectively on HIFIm. This suggests that HIFIm could equally be a potent countermeasure for use in ESA's para-astronaut project.

In this study we also tested the hypothesis that the HIFIm design would be able to minimise the force transmission between the jump sled and the aircraft. This hypothesis was supported as force transmission was generally negligible in microgravity apart from a consistent spike in the force between HIFIm and the aircraft when the user first landed on the force plate that was of a magnitude of approximately 500N (Figure 3). It is highly likely that the engineering of HIFIm can be further optimised to also bring this impact spike down to negligible levels. Future work is needed to understand the degree to which this force transmission is sensitive to the distribution of mass within HIFIm, the direction of propulsive forces during jumping and the fixation of HIFIm to the aircraft.

The mean peak eGRF seen in this study for normal jumping were typically between 600 and 1000N and were generally greater when spring resistance was increased (Figure 2). These forces are considerably lower than those that were reported as being seen during the operation of the jump sled used in the ESA long-term bed-rest study [6,14]. In particular, Kramer and colleagues [14] reported that sled jumping forces resulted in a peak GRF that was approximately 79% of the magnitude seen in normal vertical jumping – i.e. around 2750N. However, it is important to note that the participants in the Kramer study were given the instruction to jump as stiffly as possible, minimising the ground contact time. This is a very different style of jumping to that used in the majority of the parabolas in this study. Notably, we did ask participants to jump in a more similar style to that used in Kramer's study for two parabolas of the final set. We found that this style of jumping produced considerably greater eGRFs than were seen in the first two sets, and that this increase was seen despite the fact that the lowest spring resistance was used for this set. For instance, the mean peak eGRFs seen for normal jumping in set 3 were between 300 and 800N but were 1000 to 1200N for the stiffer rebounding style (Figure 5).

It thus seems likely that eGRFs that approach those seen in the Kramer study [14] could be produced if the user was instructed to produce as stiff a contact as possible against the maximum spring resistance. However, the question remains as to whether this is the appropriate way to use HIFIm. It is true that the protocol used in the ESA bed-rest study was highly successful in mitigating the deconditioning effect of bed-rest, and that this effect was seen when using the Kramer jump sled. However, the training protocol in that study comprised both stiff and normal jumps and so it is impossible to know if one or other of the jumps were more effective. The wider issue is that it is largely unknown what type of loading produces the greatest osteogenic response. The state of the art within the literature is to calculate the osteogenic index of exercise which is based upon the peak GRF and the number of impacts [17]. However, it is well established that the actual stimulus to osteogenesis is dynamic strain of the bone [18]. The formula for the osteogenic index is based upon the implicit assumption that there is a linear relationship between the peak GRF and the strain of the affected bones. Because the direct measurement of bone strains is highly invasive, there is a dearth of material that have explored the relationship between peak GRF and bone strain. However, it has been suggested that humans adjust their movement strategy to keep peak strains below a threshold level even during vigorous activity [19]. For instance, Milgrom and colleagues [20] found that there were no differences in the strain experienced when performing drop jumps from 26, 39 and 52 cm and that the strain experienced in the highest drop jumps was similar to that experienced when running at 17 km/h. The peak GRF is just one of the variables that are important in influencing the peak strain and thus much more research is needed to determine the optimal loading parameters required to induce an osteogenic response. Once this is known, it seems likely that exercise on HIFIm can be optimised to provide this stimulus.

We found that the activation of the quadriceps and gastrocnemius muscle groups was very high during exercise on HIFIm – often over 100% of MVC – and the activity of the glutes was moderate. Taken as a whole, this indicates that the exercise was of considerable intensity, with substantial tension being generated within the prime movers. Intensity and time under tension are key factors which affect the development of both muscle strength and hypertrophy [21], and so these results also suggest that jumping exercise on HIFIm is also likely to be effective for maintaining muscle strength and mass, as well as other connective tissues.

Two clear potential limitations of this work are the small subject numbers and the heterogeneous nature of the sample, both of which compromise the statistical power of the study. Clearly, parabolic flights represent an expensive experimental platform and so the number of parabolas available for testing were limited as were the number of seats available to us on each flight. Taken together these factors constrained the sample size. As the principal aim of this study was to establish the feasibility of repeated horizontal jumping as an exercise countermeasure we chose to recruit a heterogeneous sample in order to demonstrate that a diverse range of people could use HIFIm in microgravity. Between 1998 and 2013, the age of male astronauts to the ISS was between 34 and 60 years and the age of female astronauts was between 30 and 56 years [22], thus the ages of the subjects in this study (male: 35, 51 and 52 years; female 30 and 35 years) are representative of a typical astronaut cohort. Equally, given ESA’s intention to explore the feasibility of para-astronauts, future missions to low earth orbit may require exercise countermeasures that can be used by para-astronauts. This was the rationale for including an amputee among our test users.

The work reported in this study has both qualified the HIFIm exercise device to a Technology Readiness Level of 6 and repeated horizontal jumping to a Countermeasure Readiness Level of 7. In addition, although this study has focused on the use of HIFIm to perform repeated horizontal jumping it should be noted that HIFIm is a very flexible multi-modal exercise device. HIFIm can be used to perform a wide range of upper and lower body exercises, and has been designed to provide a varied range of stresses to the structures of the musculoskeletal system that are particularly prone to deconditioning. The combination of these factors make HIFIm a leading candidate to replace the Advanced Resistive Exercise Device (ARED) which has been in service since 2009. In addition, ESA have shown that short bouts of intense jumping activity are also effective in maintaining measures of cardiovascular fitness during long-term bed-rest [6] and thus HIFIm has the potential to also replace the T2 Combined Operational Load Bearing External Resistance Treadmill (COLBERT) and the Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS). The prospect of replacing three exercise machines with one all-purpose device is a clear advantage of HIFIm.

In summary, this work shows that repeated horizontal jumping is possible in microgravity using the HIFIm jump sled. These results also provide proof of concept for the HIFIm engineering approach, and suggest that force transmission can be minimised by this design. This work is an important step forward in the realisation of repeated jumping as an exercise countermeasure. Future work is needed to understand the key loading parameters that produce the optimal osteogenic response such that exercise on HIFIm can be optimised accordingly.

ACKNOWLEDGMENTS

Special thanks to Libby Jackson, Jon Scott, Dave Green and Nora Petersen for their wisdom and advice during this project. We would also like to thank CNES for the provision of an earlier Parabolic Flight Campaign.

FUNDING AND CONFLICTS OF INTEREST

This work was supported by the UK Space Agency (grants: ST/W002248/1, ST/V002996/1 and ETD007) and the experimental platform was provided by ESA.

John Kennett is the inventor of the HIFIm jump sled that was used in this work.

DATA AVAILABILITY STATEMENT

The data described in this study is available on the Open Science Framework website:

https://osf.io/mcdx6/

doi: 10.17605/OSF.IO/MCDX6

REFERENCES

1 Narici MV, de Boer MD. Disuse of the musculo-skeletal system in space and on earth. *Eur J Appl Physiol* 2011;**111**:403–20. doi:10.1007/s00421-010-1556-x

2 Rittweger J, Albracht K, Flück M, *et al.* Sarcolab pilot study into skeletal muscle's adaptation to long-term spaceflight. *NPJ Microgravity* 2018;**4**:18. doi:10.1038/s41526-018-0052-1

3 Sibonga JD, Spector ER, Johnston SL, *et al.* Evaluating Bone Loss in ISS Astronauts. *Aerosp Med Hum Perform* 2015;**86**:A38–44. doi:10.3357/AMHP.EC06.2015

4 Moore AD, Downs ME, Lee SMC, *et al.* Peak exercise oxygen uptake during and following long-duration spaceflight. *APSselect* 2014;**1**:231–8. doi:10.1152/japplphysiol.01251.2013@apsselect.2014.1.issue-9

5 Petersen N, Jaekel P, Rosenberger A, *et al.* Exercise in space: the European Space Agency approach to in-flight exercise countermeasures for long-duration missions on ISS. *Extreme Physiol Med* 2016;**5**:9. doi:10.1186/s13728-016-0050-4

6 Kramer A, Gollhofer A, Armbrecht G, *et al.* How to prevent the detrimental effects of two months of bed-rest on muscle, bone and cardiovascular system: an RCT. *Sci Rep* 2017;**7**:13177. doi:10.1038/s41598-017-13659-8

7 Kramer A, Kümmel J, Mulder E, *et al.* High-Intensity Jump Training Is Tolerated during 60 Days of Bed Rest and Is Very Effective in Preserving Leg Power and Lean Body Mass: An Overview of the Cologne RSL Study. *PloS One* 2017;**12**:e0169793. doi:10.1371/journal.pone.0169793

8 Ritzmann R, Freyler K, Kümmel J, *et al.* High Intensity Jump Exercise Preserves Posture Control, Gait, and Functional Mobility During 60 Days of Bed-Rest: An RCT Including 90 Days of Follow-Up. *Front Physiol* 2018;**9**:1713. doi:10.3389/fphys.2018.01713

9 Kohrt WM, Barry DW, Schwartz RS. Muscle Forces or Gravity: What Predominates Mechanical Loading on Bone? *Med Sci Sports Exerc* 2009;**41**:2050–5. doi:10.1249/MSS.0b013e3181a8c717

10 O'Bryan SJ, Giuliano C, Woessner MN, *et al.* Progressive Resistance Training for Concomitant Increases in Muscle Strength and Bone Mineral Density in Older Adults: A Systematic Review and Meta-Analysis. *Sports Med Auckl NZ* Published Online First: 24 May 2022. doi:10.1007/s40279-022-01675-2

11 Layne JE, Nelson ME. The effects of progressive resistance training on bone density: a review. / Effets d'un entrainement progressif de musculation sur la densite osseuse: revue. *Med Sci Sports Exerc* 1999;**31**:25–30.

12 Suchomel TJ, Nimphius S, Bellon CR, *et al.* The Importance of Muscular Strength: Training Considerations. *Sports Med Auckl NZ* 2018;**48**:765–85. doi:10.1007/s40279-018-0862-z

13 Schoenfeld BJ, Grgic J, Ogborn D, *et al.* Strength and Hypertrophy Adaptations Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. *J Strength Cond Res* 2017;**31**:3508–23. doi:10.1519/JSC.0000000000002200

14 Kramer A, Ritzmann R, Gollhofer A, *et al.* A new sledge jump system that allows almost natural reactive jumps. *J Biomech* 2010;**43**:2672–7. doi:10.1016/j.jbiomech.2010.06.027

15 Cushion EJ, Warmenhoven J, North JS, *et al.* Principal Component Analysis Reveals the Proximal to Distal Pattern in Vertical Jumping Is Governed by Two Functional Degrees of Freedom. *Front Bioeng Biotechnol* 2019;**7**. doi:10.3389/fbioe.2019.00193

16 Price PDB, Gissane C, Cleather DJ. Reliability and minimal detectable change values for predictions of knee forces during gait and stair ascent derived from the FreeBody musculoskeletal model of the lower limb. *Front Bioeng Biotechnol* 2017;**5**:74. doi:10.3389/fbioe.2017.00074

17 Turner CH, Robling AG. Designing Exercise Regimens to Increase Bone Strength. *Exerc Sport Sci Rev* 2003;**31**:45–50.

18 Turner CH. Three rules for bone adaptation to mechanical stimuli. *Bone* 1998;**23**:399–407. doi:10.1016/S8756-3282(98)00118-5

19 Burr DB. In vivo measurement of human tibial strains during vigorous activity. *Bone* 1996;**18**:405–10.

20 Milgrom C, Finestone A, Levi Y, *et al.* Do high impact exercises produce higher tibial strains than running? Br. J. SPORTS Med. 2000;**34**:195–9. doi:10.1136/bjsm.34.3.195

21 Borde R, Hortobágyi T, Granacher U. Dose-Response Relationships of Resistance Training in Healthy Old Adults: A Systematic Review and Meta-Analysis. *Sports Med Auckl NZ* 2015;**45**:1693–720. doi:10.1007/s40279-015-0385-9

22 Goel N, Bale T, Epperson C, *et al.* Effects of Sex and Gender on Adaptation to Space: Behavioral Health. *J Womens Health 2002* 2014;**23**. doi:10.1089/jwh.2014.4911