Modeling the benefits of an artificial gravity countermeasure coupled with exercise and vibration

Mr. Rahul Goel
Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, United States
rahulg@mit.edu

Mr. Justin Kaderka
Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, United States
jkaderka@mit.edu

Prof. Dava Newman
Professor of Aeronautics and Astronautics and Engineering Systems, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, United States
dnewman@mit.edu

ABSTRACT

The current, system-specific countermeasures to space deconditioning have had limited success with the musculoskeletal system in long duration missions. Artificial gravity (AG) that is produced by short radius centrifugation has been hypothesized as an effective countermeasure because it reintroduces an acceleration field in space; however, AG alone might not be enough stimuli to preserve the musculoskeletal system. A novel combination of AG coupled with one-legged squats on a vibrating platform may preserve muscle and bone in the lower limbs to a greater extent than the current exercise paradigm. A numerical model was developed to analytically analyze benefits of the proposed countermeasure. Ground reaction force data and motion data were collected using a motion capture system while performing one-legged and two-legged squats in 1-G. The motion was modeled in OpenSim, an open-source software, and inverse dynamics were applied in order to determine the muscle and reaction forces of lower limb joints. Vibration stimulus was modeled by adding a 20 Hz sinusoidal force of 0.5 body weight to the force plate data. From the numerical model in a 1-G acceleration field, muscle forces for quadriceps femoris, plantar flexors and glutei increased substantially for one-legged squats with vibration compared to one- or two-legged squats without vibration. Additionally, joint reaction forces for one-legged squats with vibration also increased significantly compared to two-legged squats with or without vibration. Higher muscle forces and joint reaction forces might help stimulate muscle activation and bone modeling and thus might reduce musculoskeletal deconditioning. These results indicate that the proposed countermeasure might surpass the performance of the current space countermeasures and should be further studied as a method of mitigating musculoskeletal deconditioning.

Keywords: Artificial gravity, human centrifuge, biomedical modeling

1. Introduction

With NASA preparing for new and novel destinations such as near-Earth asteroids, LaGrange points and beyond, countermeasures for human deconditioning in space will play an increasingly important role in human missions. Current countermeasures on the International Space Station (ISS), such as resistive exercise on the interim Resistive Exercise Device (iRED) or Advanced Resistive Exercise Device (ARED), treadmill running, and cycling, have only proven to be partially beneficial despite over four decades of optimization. In particular, astronauts returning from six months aboard the International Space Station (ISS) have shown that anti-gravity muscle volume and peak power still decrease significantly versus pre-flight (-13% and -32%, respectively) [1]. Bone mineral density (BMD) and strength losses also persist in the lower extremities with integral hip BMD being lost at an average of 1.5% per month [2, 3]. Such losses must be blunted to ensure safety of astronauts for extended duration excursions beyond low-Earth orbit.

Artificial gravity (AG) has the potential to be an effective countermeasure because it simulates gravity in space, which is created by either a rotating spacecraft or a Short Radius Centrifuge (SRC). A rotating spacecraft would be ideal from a countermeasure standpoint because a constant acceleration of 1-G could be provided; however a rotating spacecraft would require a significant departure from current spacecraft designs. AG created by an SRC continues to have the potential to be an effective countermeasure for microgravity because current concepts are less mass and volume prohibitive than a rotating spacecraft.

AG creates an acceleration that loads the bones and muscles similar to gravitational acceleration on Earth. AG also reintroduces hydrostatic gradients in the body and causes a fluid shift toward the lower extremities. Aside from being greatly beneficial to the cardiovascular system [4, 5], hydrostatic gradients also cause an increase in blood flow to muscles of the lower body [6]. In addition, the fluid shift is potentially important to bone remodeling. Osteocytes are believed to act as strain receptors by sensing changes in interstitial fluid due to loading [7]. Decreased interstitial fluid, which occurs in the lower limbs in bed rest studies [6], in theory, attenuates the ability of osteocytes to act as strain receptors. Artificial gravity reverses this trend and therefore has the potential to greatly benefit the skeletal system. In addition, the current exercise countermeasures on the space station utilize elastic straps and harnesses to load the body and to restrain the crewmembers. The harnesses create an unnatural and often uncomfortable load on the shoulders and back, which limits body loading. AG is advantageous because it creates a more natural loading that can easily be increased to levels in excess of 1-G.

1.1. Artificial gravity as a countermeasure to musculoskeletal deconditioning

There are an extremely limited number of AG studies in space. Almost all of the studies have been on rats in the Soviet Biosatellite ‘Cosmos’ program [8]. However, there have been a number of ground-based analog studies utilizing either bed rest or animal models to simulate microgravity. A recent analysis of these ground-based, deconditioning studies has indicated that AG has performed as effectively as the current types of countermeasures aboard the ISS for the cardiovascular system [9]. Nevertheless, few of these studies have focused on the efficacy of AG on muscles of the lower limbs and even fewer have focused on skeletal effects.

Bed rest studies with passive AG (i.e. AG not coupled with exercise) have shown a substantial decrease in muscle atrophy (cross-sectional area) in the vastus lateralis and significant decrease in muscle atrophy in the soleus [10]; however, results on bone parameters have been inconclusive [11]. As there is a paucity of human AG studies on the musculoskeletal system, animal hind limb suspension models coupled with centrifugation provide an analog. Some of these studies have shown that one hour/day of 1.5-Gx can significantly attenuate muscle atrophy in rats [12].

1.2. Enhancing the effect of artificial gravity with exercise

Few studies have evaluated the effectiveness of exercise coupled with AG to counteract musculoskeletal deconditioning. In a bed rest study, Akima et al. [13] showed AG coupled with intensive cycle training maintained thigh muscle size but not strength. Other studies, which couple AG with squats or stair steppers, have evaluated muscle activation and the feasibility of conducting these exercises in a rotating environment [14, 15].

1.3 Enhancing the effect of artificial gravity with vibration

Vibration exercise, in which subjects are pressed against a platform vibrating at frequencies of 20-45 Hz and amplitudes between 1.5-6 mm, has also been evaluated to counteract muscle and bone atrophy [16]. Whole body vibration proved capable of maintaining calf muscle strength and fiber type composition during a 55-day bed rest study [17]. Vibration exercise has also been shown to increase muscle activation by $360.6 \pm 57.5\%$ and $151.4 \pm 19.5\%$ for the gastrocnemius and rectus femoris, respectively, while subjects performed one- and two-legged squats [18]. Additionally, vibration exercise coupled with one- and two-legged squats was shown to increase knee extensor maximum isometric strength in postmenopausal women by 15% ($p<0.01$) and increase hip bone mineral density (BMD) by 0.93% ($p<0.05$) in a 6 month study [19]. Finally, peak acceleration of up to 0.2g with a frequency of 20 Hz has been found to be effective in reducing postmenopausal bone loss [20].

It is theorized that skeletal remodeling is mediated by osteocyte strain receptors in the bone [7]. Additionally, some evidence has shown that the magnitude of strain is the pertinent factor, not strain frequency [21], though it is still a matter of much debate. Since bone strain is a function of applied force and bone geometry, for the same person an increase in loading will produce higher strains. Vibration can increase skeletal loading through direct mechanical impact and through increased muscle activation and therefore provide a strong stimulus for the maintenance of bone strength. Resistive vibration exercise in addition to high-load resistive exercises (including squats), were found to be effective in reducing muscle atrophy in the extensors of the knee and ankle [22].

A novel combination of AG with one-legged squats and vibration exercise is proposed to counteract the musculoskeletal deconditioning commonly seen in prolonged exposure to microgravity. The authors hypothesize that performing one-legged squats on a vibrating platform while in an AG environment will generate higher muscle and joint forces than the ISS exercises, thus creating a greater prophylactic effect.

2. Methods

The primary goal of the present analysis was to determine the biomechanics of one-legged and two-legged squats performed on a simulated vibrating platform. In order to determine the muscle forces and loads on the hip, the squat motion was modeled in OpenSim (Stanford, CA) [23] – an open-source software system that has well-developed models of musculoskeletal structures and allows users to create dynamic simulations of motion – and inverse dynamics was carried out to compute the muscle activity. Figure 1 shows the work flow to obtain muscle forces from motion capture data.

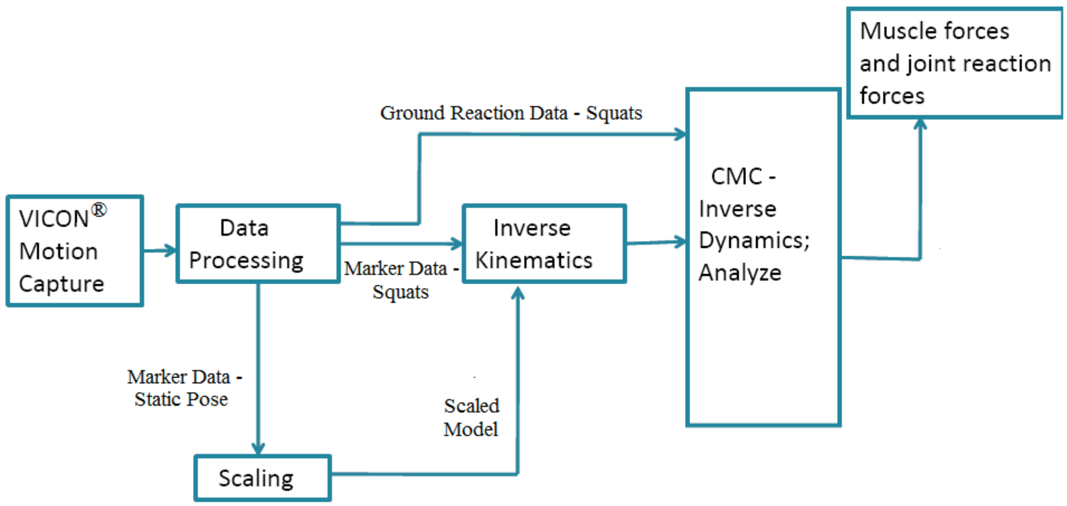

Fig. 1. Work flow to obtain muscle forces from motion capture data of squats.

2.1 Data collection

All experiments were performed at the Computer Science and Artificial Intelligence Laboratory at MIT using the Vicon® (Los Angeles, USA) motion capture system. Four male subjects (26 ± 6 years old) participated in the experiment and were of similar stature (718 ± 8 N in weight and 176 ± 5 cm tall). Forty-five markers were placed at the Helen Hayes marker locations [24] on the subject's body while 16 cameras tracked the movement as the subject performed squats. Ground reaction force (GRF) and moment data were obtained from two force plates. Two-legged squats were performed with each foot placed on the center of each force plate while one-legged squats were performed with one foot around the center of one force plate. While performing one-legged squats, the non-weight bearing leg was extended to the front as illustrated in Figure 2. For both squats, subjects performed one squat (eccentric and concentric phases) in approximately three seconds. Subjects were instructed to descend into the squat until the femur was approximately parallel to the floor. Subjects performed a series of four squats of each type and the optimal squat for each type was chosen for subsequent analysis. One-legged squats were performed with both right and left legs; however, results of only the right leg are presented as the right leg was dominant for all subjects. Analog data from the force plate was recorded at 1000 Hz, whereas the video data of marker locations was recorded at 120 Hz.

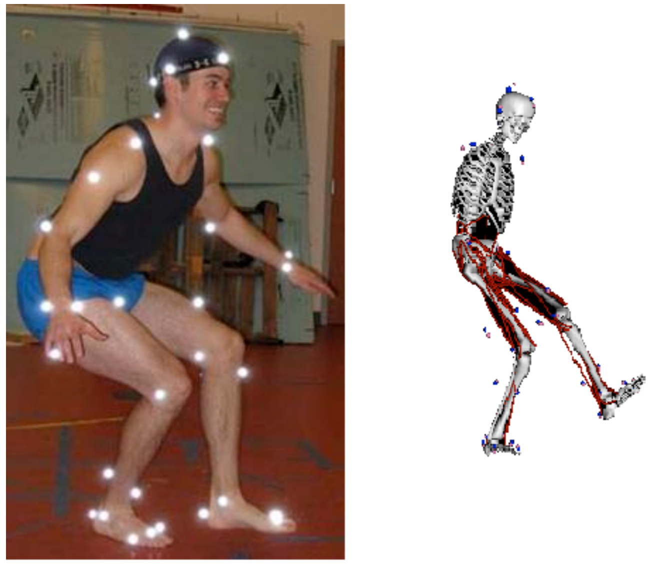

Fig. 2. Motion capture experiment and modeling.

2.2. Data analysis

OpenSim was used to determine muscle forces and activations. MATLAB scripts were developed to convert Vicon® data into acceptable inputs for OpenSim. Before performing inverse kinematics in OpenSim, it was first necessary to scale the model to the anthropometric dimensions of the subject (Figure 1). For this purpose, marker positions were collected with the subject in a static pose, in which the subject stood still with knees straight and arms extended to the front. The scaling tool in OpenSim used this data to appropriately adjust the lengths of different body segments and then adjust the model markers (i.e. markers on the simulated skeleton in OpenSim) to be as close as possible to the experimental markers (i.e. markers placed on the subject). After scaling, inverse kinematics was performed; this replicated the motion of the subject in the numerical model.

The GRF and moments along with the joint angles, which were obtained from Inverse Kinematics, were used to run the Computed Muscle Control (CMC) tool in OpenSim. CMC first generates the joint torques required to perform the simulated motion. It then uses a static optimization algorithm to find appropriate muscle activation levels and forces. In some instances, the optimization determined some muscles reached their maximum isometric force; this was solved by increasing the maximum isometric force for that muscle. This step was necessary because of subject variability in muscle strength. Unfortunately, it was not possible to modify gravity in OpenSim to simulate the gradients a subject would normally experience while performing squats on a short radius centrifuge.

2.3. Simulation of a body platform

In order to model the effect of a vibrating platform at the feet, the force plate data was modified to include a sinusoidal force:

$$F = BWx0.5\sin\left(20x2\pi t\right) \tag{1}$$

where BW is the body weight in Newtons. This force due to vibration was added to the ground reaction force. A frequency of 20 Hz was used because it is a typical frequency used in vibration studies [16], and the computational limitations of OpenSim prevented the use of a higher frequency. A maximum force of BW*0.5 that was transferred to the feet was used as a proof-of-concept.

A comparison of muscle forces generated in quadriceps femoris, plantar flexors and glutei was performed for two-legged and one-legged squats both with and without added vibration. Table 1 shows the various muscles of interest.

Table 1
Relevant muscle groups and their associated muscles.

Quadriceps femoris	**Plantar flexors**	**Glutei**
Rectus femoris	Soleus	Gluteus maximus
Vastus lateralis	Medial gastrocnemius	Gluteus medius
Vastus medialis		Gluteus minimus
Vastus intermedialis		

2.4. Analysis of loads applied to bone

It is believed that strain in bone activates bone modeling. Strain is a function of the bone load and the bone geometry, and can be determined through finite element models (FEM) or in vivo strain gauging on the surface of the bone [25, 26]. However, for the same bone geometry a higher load will cause a higher strain. Therefore, bone loads in the main weight bearing bone (femoral axial strains) were examined. Joint reaction forces at the hip were analyzed using Analyze tool of OpenSim. Forces were calculated along the direction of femur.

2.5. Statistics

All data was tested for normality using the Kolmogorov-Smirnov test. A T-test for dependent samples was used and significance was taken at the $p = 0.05$ level. All data is presented as the average ± SE.

3. Results

3.1. Ground Reaction Forces

Peak GRFs for one- and two- legged squats were obtained from force plate data. For two-legged squats the peak GRF is the average of the two legs. Average peak GRF for two-legged squats for the four subjects was 453.7 ± 24.4 N (0.63 ± 0.03 BW) and was 832.8 ± 35.7 N (1.16 ± 0.05 BW) for one-legged squats.

3.2. Muscle forces

Figure 3 shows a representative time history curve of the muscle forces of plantar flexors for one-legged squats both with and without vibration (Vib). It is plotted around the point of interest, which is the maximum knee flexion (shown by a dash line). In general, forces tend to peak at the end of the descent phase of the squat during maximum knee flexion.

The average maximum knee flexion angle for the four subjects for two-legged squats was found to be 114.7 ± 4°. Similarly, the average maximum knee flexion angle for the four subjects for one-legged squats was found to be 100 ± 8.8°.

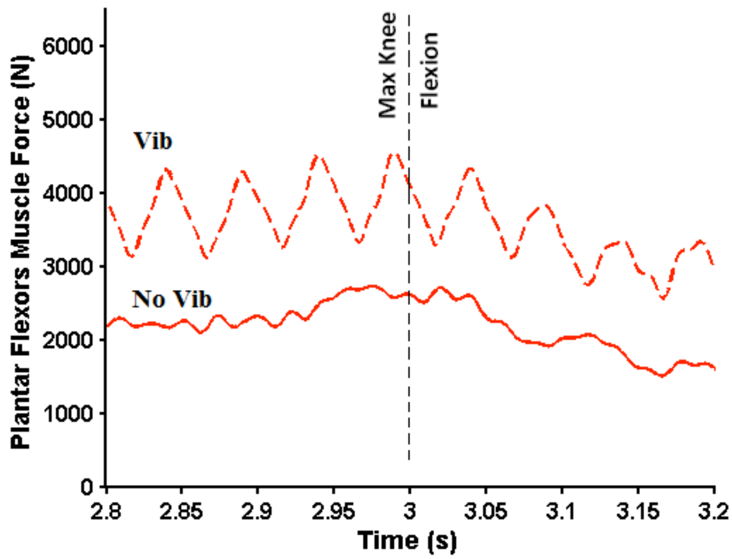

Fig. 3. Representative curve of muscle forces of plantar flexors showing comparison for one-legged squat with and without vibration.

Figures 4-6 show box plots of computed peak muscle forces for the three muscle groups across four conditions (one-legged or two-legged squats, either with or without vibration). Peak muscle forces for glutei and quadriceps femoris were significantly higher for one-legged squats without vibration compared to two-legged squats without vibration ($p = 0.006$ for both). However, this was not significant for the plantar flexors ($p = 0.41$).

Vibration did not have an effect in two-legged squats for any muscle group (glutei, $p = 0.43$; quadriceps femoris, $p = 0.097$; plantar flexors, $p = 0.22$). However, vibration was effective in one-legged squats for all muscle groups ($p < 0.05$). Finally, muscle forces in one-legged squats with vibration were significantly different than those of two-legged squats with vibration for all the muscle groups ($p < 0.05$).

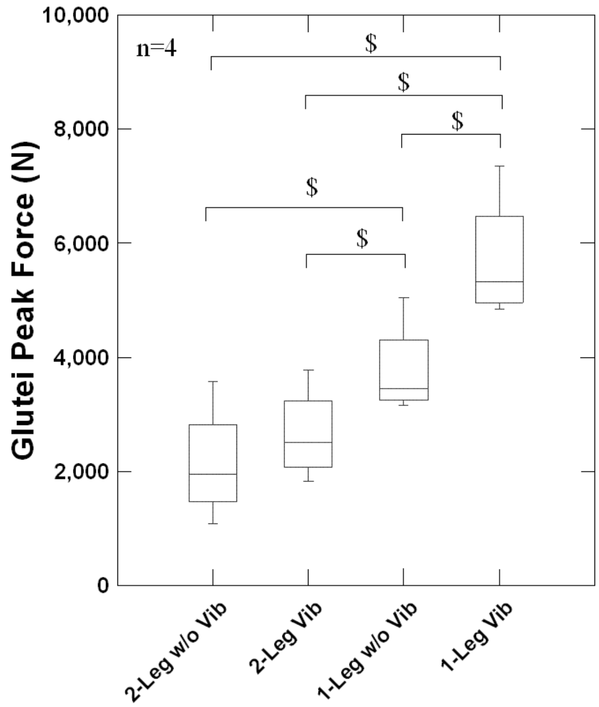

Fig. 4. Peak muscle forces for the glutei for the four conditions. $:- p<0.05

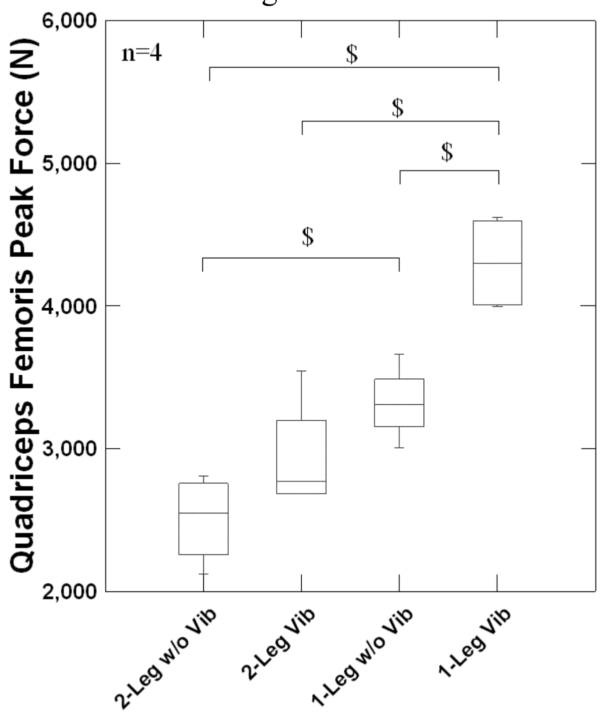

Fig. 5. Peak muscle forces for the quadriceps femoris for the four conditions. $:- p<0.05

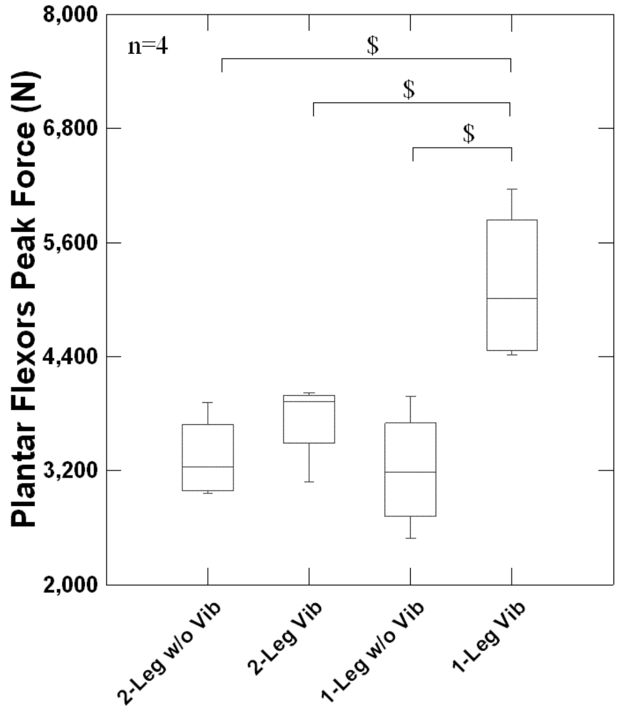

Fig. 6. Peak muscle forces for the plantar flexors for the four conditions. $:- p<0.05

3.3. Joint reaction forces

Figure 7 shows a representative curve of the computed hip joint reaction forces that are axial to the femur and compares one-legged squat with and without vibration. Forces are plotted around the point of maximum knee flexion (shown by a dash line).

Figure 8 shows box plots of peak hip joint reaction force for the four conditions. Joint reaction forces are not significantly different between two-legged squats with or without vibration ($p = 0.787$). Contrary to the muscle forces, vibration was also not significant between joint reaction forces of one-legged squats with or without vibration ($p = 0.33$). Vibration is effective however between two-legged and one-legged squats ($p = 0.016$).

A summary of muscle forces and joint reaction forces that were examined is shown in Table 2.

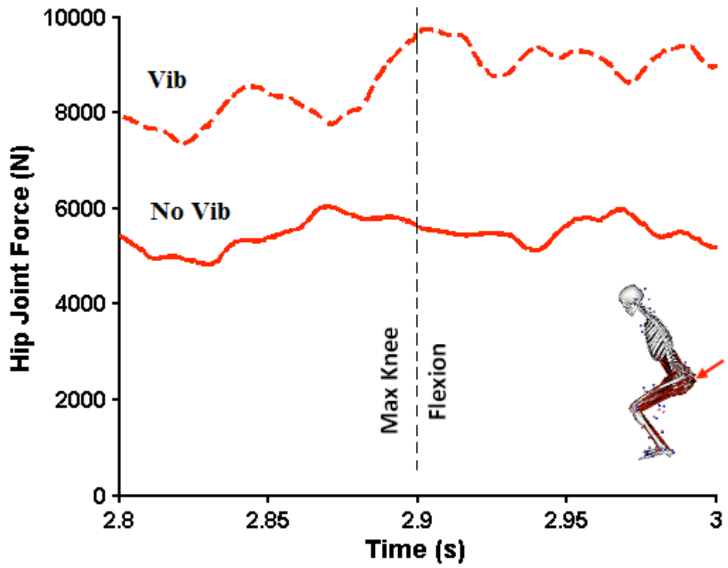

Fig. 7. Joint reaction force comparison for one-legged squat with and without vibration.

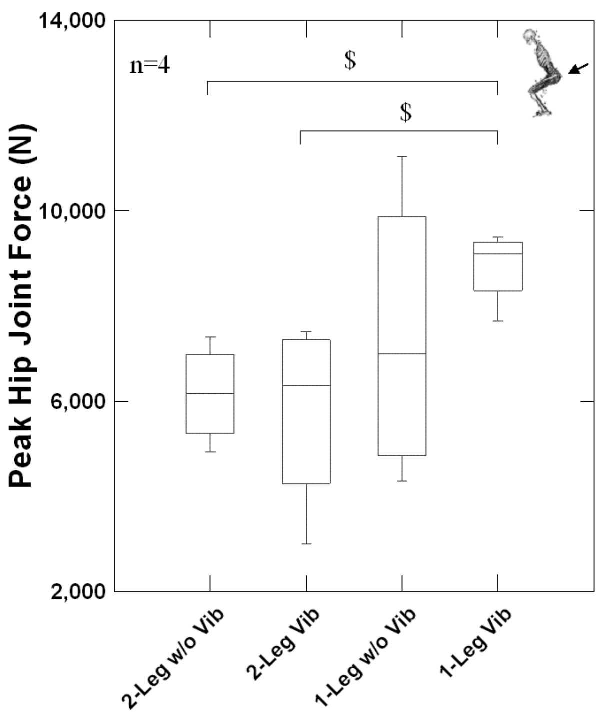

Fig. 8. Peak axial hip joint reaction forces for the four conditions. $:- p<0.05

Table 2
Average peak forces for gluteal muscles, quadriceps femoris, plantar flexors, and hip joint.

	Gluteal muscles (N)	**Quadriceps femoris (N)**	**Plantar flexors (N)**	**Hip joint (N)**
2-Leg w/o Vibration	2143 (523)	2760 (234)	3339 (223)	6153 (526)

2-Leg w/ Vibration	2656 (414)	3413 (307)	3740 (219)	5782 (1016)
1-Leg w/o Vibration	3781 (432)[a,b]	3982 (201)[a]	3211 (319)	7293 (1600)
1-Leg w/ Vibration	5717 (569)[a,b,c]	5454 (253)[a,b,c]	5152 (418)[a,b,c]	8832 (396)[a,b]

[a]$p < 0.05$ vs. one-legged squat without vibration, [b]$p < 0.05$ vs. one-legged squat with vibration, [c]$p < 0.05$ vs. two-legged squat without vibration.

4. Discussion

4.1 Evaluation of physiological effects of combined AG, exercise and vibration countermeasure

In order to assess the effectiveness of the proposed countermeasure, ground reaction forces, muscle forces, and joint reaction forces must be compared to iRED and normal 1-G activity. If this proposed countermeasure is capable of exceeding the loading environment created when the iRED is used in microgravity, then muscle and bone strength might be maintained to a greater extent than currently observed with astronauts on the ISS.

The maximum GRF per leg, which was produced from two-legged squats on iRED in parabolic flight, was 340 N, or nearly 0.5 BW [27]. In the present study, the GRFs produced per leg during a one-legged squat were 144% higher than from a two-legged squat using iRED. Similarly, GRFs from two-legged squats in this study were 33% higher than from two-legged squat on iRED. The largest GRF experienced by the subject in this study was 1.2 BW. Peak GRF experienced when walking in 1-G is 1.5 BW [28]. When accounting for the maximum 0.5 BW that is added to simulate a vibrating platform (peak GRF = 1.7 BW), the GRF of this study exceeds that of 1-G walking. In a recent study, average single leg forces for two-legged squat using iRED on the ISS was found to be 0.59 BW, and that for one-legged squat was found to be 0.64 BW [29].

To the authors' knowledge, studies on muscle activation or joint reaction forces while using the ARED or iRED in microgravity have not been published, which precludes direct comparison to the proposed countermeasure. However, a comparison to squat biomechanics in 1-G is useful because that is the condition the proposed countermeasure would mimic or exceed. Dahlkvist et al. [30] performed two-legged squats and recorded average force in several muscle groups of eight subjects. In the Dahlkvist study, the maximum force of the quadriceps femoris was 4701 N compared to 3214 N in the present study during two-legged squats without vibration. Conversely, average muscle force for the gastrocnemius was 950 N in the Dahlkvist study and 2859 N in the present study. Finally, average peak force for hamstrings was 1640 N in the Dahlkvist study while the average force was 2200 N in the present study. Overall, there seems to be an agreement between muscle forces in these two studies. In an analytical model developed by Zheng et al. [31], maximum force estimated in quadriceps femoris was 3500 N at maximum knee flexion of 85 deg.

Muscle group forces during one-legged squats with vibration were found to be significantly higher than the other three conditions. However, since no significant difference was found between two-legged squats with and without vibration, the salutary effects of vibration seem to appear primarily with one-legged squats. Although joint reaction forces increased by only 21% during one-legged squats with application of vibration, muscle forces increased substantially (glutei, 52%; quadriceps femoris, 37%; plantar flexors, 60%). This finding suggests a strongly enhanced stimulus to muscle activation.

Simulated vibration exercise was confirmed to be a highly effective stimulant for both muscle and bone, as demonstrated by the considerable increase in muscle forces and joint reaction forces. Most strikingly, the force in plantar flexors for one-legged squats is increased by 60% after the addition of vibration. This large, salutary effect with the application of vibration is important since the plantar flexors are important antigravity muscles that undergo significant deconditioning in space.

Peak acceleration in human vibration studies reviewed by Rittweger [16] was 157 m/s^2 or 16 BW (40 Hz, 2.5 mm). However, OpenSim is unable to process these high accelerations. Because 0.5 BW was used as a proof-of-concept, the muscle activation resulting from vibration is potentially an underestimation of what can be achieved.

Intermittent AG, both passive and coupled with exercise, has shown some promising results with muscle parameters such as cross-sectional area and muscle molecular markers [9, 10]. However, complete preservation of these parameters has not been achieved. In addition, AG thus far has shown to have a minimal effect on bone properties. Vibration could offer the necessary stimulus to further attenuate muscle degradation as well as preserve bone density.

4.2 Limitations

Some limitations were faced in the experimental design mainly due to practical issues, time constraints and the lack of physiological data from the ISS with which to compare the results of the present study. Firstly, this experiment did not directly assess the ability of the exercise to prevent deconditioning, as this would have required weeks of bed rest and many subjects. Instead, conclusions are based on the relative muscle activation and joint reaction forces produced from the numerical model and compared to those of iRED studies and ground-based studies. It must be noted that the physiology of musculoskeletal deconditioning is complex and cannot be completely assessed by the magnitude of the stimulus to bone and muscle; however, muscle forces and joint reaction forces are a contributing factor and have been chosen since they are some of the most frequently analyzed measurements.

In addition, squat experiments were performed in 1-G rather than on a rotating centrifuge because the Vicon motion capture system used had to be conducted in a stationary environment. Therefore, the Coriolis forces and gravity gradients were not present in the modeling of the kinematics and dynamics. However, Duda [14] determined that Coriolis forces and gravity gradients do not significantly affect two-legged squat biomechanics during centrifugation. Also, it was not possible to simulate in OpenSim accelerations greater than 1-G, which is common in AG experiments [9], and would produce higher muscle and joint forces and thus improve the effectiveness of the exercise protocol.

Finally, because we did not have access to a vibrating platform, all experiments were performed while standing on stationary force plates and vibration was simulated in OpenSim. The accuracy of this method depends on the assumption that the subject’s kinematics would not have changed if the exercise was performed with vibration. This assumption appears to be valid based on studies that have indicated the vibration is hardly discernable [20].

4.3. Feasibility

Artificial gravity has the potential to be a comprehensive countermeasure although a human centrifuge has yet to be implemented in space. This has been based on a number of reasons including spacecraft volume constraints and programmatic restraints. Due to power limitations foreseen in exploration class missions, a centrifuge in space might be confined to only use human power. Cycling has been the only modality proven to be capable of human-powering a centrifuge ('The space cycle' [32]). While this necessitates a cycle ergometer be used on one arm of the centrifuge, a two-arm centrifuge could utilize the second arm as a vibrating platform for squats and calf presses. Thus crewmembers could utilize AG coupled with cycling for a cardiovascular countermeasure and AG coupled with squats and vibration for a musculoskeletal countermeasure. When crewmembers are sent to points of interest away from low Earth orbit for long duration missions, a more effective countermeasure system will be required; AG coupled with squats and vibration might be such a countermeasure for the musculoskeletal system.

Another practical constraint to the proposed design is additional crew time required to perform one-legged squats as opposed to two-legged squats. It is assumed that no additional centrifugation time will be required. Because one-legged squats are more strenuous, it is likely that the subject will not be able to perform as many repetitions as would be possible with two-legged squats. The described countermeasure suggests one-legged squats because the exercise is more demanding and creates higher loads than two-legged squats. Higher muscle activation, which is caused by the body's weight being lifted by one leg instead of two, will increase bone loading and thus strain. As a result, one-legged squats might prevent bone degradation to a greater extent than two-legged squats.

4.4. Recommendations

The work presented herein demonstrates the potential of AG coupled with exercise and vibration to prevent musculoskeletal deconditioning in microgravity. Future work will be required to directly assess the ability of this proposed countermeasure to curtail muscle atrophy and bone loss. Specifically, a bed rest study should be performed in which subjects are exposed to 90 days of bed rest with or without AG coupled with exercise and vibration training. It is recommended that artificial gravity be pursued as a countermeasure because of its potential as a multi-system countermeasure.

5. Conclusions

Musculoskeletal deconditioning in microgravity is a potentially serious health risk that astronauts face on long duration missions. In order to mitigate bone loss and muscle atrophy, a countermeasure combining AG, exercise, and vibration has been proposed that will provide an enhanced stimulus to muscle and bone. The physiological effect of the exercise prescription was simulated through subject motion capture and kinematics simulation in a numerical model to determine muscle activation and joint reaction forces. It was found that the proposed countermeasure has the potential to provide higher muscle activation and joint forces than current exercise countermeasures. Finally, a novel numerical modeling technique has been proven that can be used to test the efficacy of different test protocols in advance of performing more rigorous experiments such as bed rest studies.

Acknowledgements

The authors would like to thank its four subjects, the OpenSim support team and lab colleagues (Sofia d'Orey, Roedolph Opperman, Rachel Ellman, Kavya Manyapu and Richard Rhodes) for their fruitful discussions and assistance at different stages of the project.

References

1. S. Trappe, D. Costill, P. Gallagher, A. Creer, J.R. Peters, H. Evans, D.A. Riley, R.H. Fitts, Exercise in space: human skeletal muscle after six months aboard the International Space Station, Journal of Applied Physiology 106 (2009) 1159-1168.
2. J.H. Keyak, A.K. Koyama, A. LeBlanc, Y. Lu, T.F. Lang, Reduction in proximal femoral strength due to long-duration spaceflight, Bone 44 (2009) 449-453.
3. T. Lang, A. LeBlanc, H. Evans, Y. Lu, H. Genant, A. Yu, Cortical and trabecular bone mineral loss from the spine and hip in long-duration spaceflight, Journal of Bone and Mineral Research 19 (2004), 1006-1012.
4. J. Vernikos, D.A. Ludwig, A.C. Ertl, C.E. Wade, L. Keil, D. O'Hara, Effect of standing or walking on physiological changes induced by head down bed rest: Implications for spaceflight, Aviation Space & Environmental Medicine 67 (1996), 1069-1079.
5. F. Vil'Vil'yams, E.B. Shul'zhenko, State of cardiovascular function after immersion for three days and prophylactic spinning on a short-radius centrifuge, Human Physiology 6 (1980), 150-154.
6. V.I. Korolkov, I.B. Kozlovskaya, A.R. Kotovskaya, V.P. Krotov, I.F. Vil-Viliams, V.I. Lobachik, Efficacy of periodic centrifugation of primates during 4-week head-down tilt, Acta Astronautica 49 (2001), 237-242.
7. M.J. Pead, R. Suswillo, T.M. Skerry, S. Vedi, L. E. Lanyon, Increased 3H-uridine levels in osteocytes following a single short period of dynamic bone loading in vivo, Calcified Tissue International 43 (1988), 92-96.
8. G. Clement, A.P. Traon, Centrifugation as a countermeasure during actual and simulated microgravity: a review, European Journal of Applied Physiology 92 (2004), 235-248.
9. J. Kaderka, L.R. Young, W.H. Paloski, A critical benefit analysis of artificial gravity as a microgravity countermeasure, Acta Astronautica, 67 (2010), 1090-1102.
10. V. Caiozzo, F. Haddad, S. Lee, M. Baker, W. Paloski, K. M. Baldwin, Artificial gravity as a countermeasure to microgravity: A pilot study examining the effects on knee extensor and plantar flexor muscle groups, Journal of Applied Physiology 107 (2009), 39-46.
11. S. Schneider, W.E. Amonette, K. Blazine, J. Bentley, S.M. C. Lee, J.A. Loehr, A.D. Moore, M. Rapley E.R. Mulder, S.M. Smith, Training with the International Space Station interim exercise device, Medicine & Science in Sports & Exercise 35 (2003), 1935-1945.

12. L.F. Zhang, B. Sun, X.S. Cao, C. Liu, Z.B. Yu, L.N. Zhang, J.H. Cheng, Y.H. Wu, X.Y. Wu, Effectiveness of intermittent -G x gravitation in preventing deconditioning due to simulated microgravity, Journal of Applied Physiology 95 (2003), 207-218.
13. H. Akima, K. Katayama, K. Sato, K. Ishida, K. Masuda, H. Takada, Y. Watanabe, S. Iwase, Intensive cycle training with artificial gravity maintains muscle size during bed rest, Aviation Space & Environmental Medicine 76 (2005), 923-929.
14. K. Duda, Squat exercise biomechanics during short-radius centrifugation, MIT Aero-Astro PhD Thesis, 2007.
15. J. Edmonds, Exercise protocols during short-radius centrifugation for artificial gravity, MIT Aero-Astro PhD Thesis, 2008.
16. J. Rittweger, Vibration as an exercise modality: How it may work, and what its potential might be, European Journal of Applied Physiology 108 (2010), 877-904.
17. D. Blottner, M. Salanova, B. Puttmann, G. Schiffl, D. Felsenberg, B. Buehring, J. Rittweger, Human skeletal muscle structure and function preserved by vibration muscle exercise following 55 days of bed rest, European Journal of Applied Physiology 97, (2006), 261-271.
18. M. Roelants, S.M.P., Verschueren, C. Delecluse, O. Levin, V. Stijnen, Whole-body-vibration-induced increase in leg muscle activity during different squat exercises, Journal of Strength and Conditioning Research 20 (2006), 124-129.
19. S. Verschueren, M. Roelants, C. Delecluse, S. Swinnen, D. Vanderschueren, S. Boonen, Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women: a randomized controlled pilot study, Journal of Bone and Mineral Research 19 (2004). 352-359.
20. C. Rubin, R. Recker, D. Cullen, J. Ryaby, J. McCabe, K. McLeod, Prevention of postmenopausal bone loss by a low-magnitude, high-frequency mechanical stimuli: A clinical trial assessing compliance, efficacy, and safety, Journal of Bone & Mineral Research 19 (2004), 343-351.
21. H.M. Frost, Why do marathon runners have less bone than weight lifters? A vital-biomechanical view and explanation, Bone 20 (1997), 183-189.
22. D.L. Belavy, L. Miokovic, G. Armbrecht, J. Rittweger, D. Felsenberg, Resistive vibration exercise reduces lower limb muscle atrophy during 56-day bed rest, Journal of Musculoskeletal and Neuronal Interactions 9 (2009), 225-235.
23. S.L. Delp, F.C. Anderson, A.S. Arnold, P. Loan, A. Habib, C.T. John, E. Guendelman, D.G. Thelen, OpenSim: Open-source software to create and analyze dynamic simulations of movement, IEEE Transactions on Biomedical Engineering 54 (2007), 1940-1950.
24. R.B. Davis, S. Ounpuu, D. Tyburski, J.R. Gage, A Gait analysis data collection and reduction technique, Human Movement Science, 10 (1991), 575-587.
25. S. Judex, T.S. Gross, R.F. Zernicke, Strain gradients correlate with sites of exercise-induced bone-forming surfaces in the adult skeleton, Journal of Bone Mineral Research 12 (1997), 1737-1745.
26. B.A. Rabkin, J.A. Szivek, J.E. Schonfeld, B. P. Halloran, Long-term measurement of bone strain *in vivo:* The rat tibia, Journal of Biomedical Materials Research 58 (2001), 277-281.

27. S.M.C. Lee, K. Cobb, J.A. Loehr, D. Nguyen, S.M. Schneider, Foot-ground reaction force during resistive exercise in parabolic flight, Aviation Space & Environmental Medicine 75 (2004), 405-412.
28. J. Nilsson, A. Thorstensson, Ground reaction forces at different speeds of human walking and running, Acta Physiologica Scandinavica 136 (1989), 217-227.
29. K.O. Genc, R. Gopalakrishnan, M.M. Kuklis, C.C. Maender, A.J. Rice, K.D. Bowersox, P.R. Cavanagh, Foot forces during exercise on International Space Station, Journal of Biomechanics (in press).
30. N.J. Dahlkvist, P. Mayo, B.B. Seedhom, Forces during squatting and rising from a deep squat, Engineering in Medicine, 11 (1982), 69-76.
31. N. Zheng, G.S. Fleisig, R.F. Escamilla, S.W. Barrentine, An analytical model of the knee for estimation of internal forces during exercise, Journal Of Biomechanics 31 (1998), 963-967.
32. Y. Yang, A. Kaplan, M. Pierre, G. Adams, P. Cavanagh, C. Takahashi, A. Kreitenberg, J. Hicks, J. Keyak, V. Caiozzo, Space cycle: a human-powered centrifuge that can be used for hypergravity resistance training, Aviation, Space, and Environmental Medicine 78 (2007) 2-9.

Author biographies

Rahul Goel

Mr. Goel received his Masters degree in Aeronautics and Astronautics from MIT. Before that Mr. Goel did his undergraduate from IIT Bombay in India majoring in Aerospace engineering. Mr. Goel is currently working with EADS Astrium in Germany. Mr. Goel is interested in space systems engineering, and specifically in the human-related aspects of spaceflight, like crew performance, space physiology, and human factors. One of his main ambitions is to fly to space, hopefully on an Indian rocket. In his free time, Mr. Goel enjoys playing tennis, squash, travelling, or reading.

Justin Kaderka

Mr. Kaderka is currently a Ph.D. candidate at MIT, where he first earned a Master of Science degree in 2010. Prior to enrolling at MIT, Mr. Kaderka worked as a Thermal Engineer at Space Systems/Loral. In 2006, Mr. Kaderka received Bachelor of Science degrees in Mechanical Engineering and Materials Science and Engineering from the University of California at Berkeley. Mr. Kaderka's main research interests are countermeasures to prevent human spaceflight deconditioning and human-machine performance prediction. Mr. Kaderka is a member of the American Institute of Aeronautics and Astronautics, and the Human Factors and Ergonomics Society.

Prof. Dava Newman

Prof. Newman is a Professor in the Department of Aeronautics and Astronautics and Engineering Systems at MIT. Prof. Newman specializes in investigating human performance across the spectrum of gravity. Prof. Newman was Principal Investigator (PI) for the Space Shuttle Dynamic Load Sensors (DLS) experiment that measured astronaut-induced disturbances of the microgravity environment on mission STS-62. Prof. Newman is an expert in the areas of extravehicular activity (EVA), human movement, physics-based modeling, biomechanics, energetics and human-robotic cooperation. Prof. Newman was named one of the Best Inventors of 2007 for her BioSuit™ system by Time Magazine.