Ground Reaction Forces During Reduced Gravity Running in Parabolic Flight

Peter Cavanagh; Andrea Rice; Molly Glauberman; Amanda Sudduth; Arien Cherones; Shane Davis; Michael Lewis; Andrea Hanson; Grier Wilt

BACKGROUND: Treadmills have been employed as both a form of exercise and a countermeasure to prevent changes in the musculoskeletal system on almost all NASA missions and many Russian missions since the early Space Shuttle flights. It is possible that treadmills may also be part of exercise programs on future Mars missions and that they may be a component of exercise facilities in lunar or Martian habitats.

METHODS: In order to determine if the ambient gravity on these destinations will provide osteogenic effects while performing exercise on a treadmill, ground reactions forces (GRFs) were measured on eight subjects (six women and two men) running at 6 mph during parabolic flight in Martian and lunar gravity conditions.

RESULTS: On average, stride length increased as gravity decreased. The first and second peaks of the GRFs decreased by 0.156 and 0.196 bodyweights, respectively, per 1/10 g change in ambient gravity.

DISCUSSION: Based on comparisons with previously measured GRF during loaded treadmill running on the International Space Station, we conclude that unloaded treadmill running under lunar and Martian conditions during exploration missions is not likely to be an osteo-protective exercise.

KEYWORDS: Mars, Moon, countermeasures, musculoskeletal, locomotion.

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Treadmills have been employed as both a form of exercise and a countermeasure to prevent changes in the musculoskeletal system on almost all NASA missions since the early Space Shuttle flights[24,28] and on many Russian missions.[12,14,29] It is possible that treadmills may also be part of exercise programs on future Mars missions and that they may be a component of exercise facilities in lunar or Martian habitats. The ground reactions forces (GRFs) in reduced gravity need to be examined in order to assess the value of treadmill running as a musculoskeletal exercise countermeasure during exploration missions. Although GRFs in treadmill running in 1 g are well characterized,[1,30] information on GRFs in reduced gravity has been primarily collected under simulated conditions or during loaded running on the International Space Station.[6,9] The purpose of the present paper is to document the GRFs generated during treadmill running in parabolic flight with parabolic flight trajectories that produce both lunar (0.17 g) and Martian gravity (0.38 g).

METHODS

Subjects

This experiment, which was approved by the University of Washington and NASA Institutional Review Boards, was conducted on a parabolic flight campaign under the auspices of NASA's Reduced Gravity Office. Eight volunteers (six women, two men; see **Table I**) who exercised regularly completed preflight medical screening.

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Table I. Subject Characteristics (by Gender) and Number of Cycles Used for Data Analysis of Running in Each Gravity Condition.

	MEN				
SUBJECT #	**HEIGHT (INCHES)**	**WEIGHT (LB)**	**LUNAR CYCLES USED**	**MARTIAN CYCLES USED**	**GROUND CYCLES USED**
1	70.5	200	21	39	107
8	70	191	30	45	73
Average	70.3	195.5	25.5	42.0	90.0
SD	0.4	6.4	6.4	4.2	24.0
	WOMEN				
SUBJECT #	**HEIGHT (INCHES)**	**WEIGHT (LB)**	**LUNAR CYCLES USED**	**MARTIAN CYCLES USED**	**GROUND CYCLES USED**
2	66	137	39	47	103
3	61	124	42	0	81
4	62	160	43	49	116
5	66.5	173	39	52	69
6	68	144	42	51	66
7	62	118	28	39	79
Average	64.3	142.7	38.8	39.7	85.7
SD	2.9	21.0	5.6	20.0	19.8

Equipment and Materials

A Kistler Gaitway split-plate (fore-aft) treadmill (Kistler Instruments, Buffalo, NY) was used for both ground and flight data collection. Ground control data (1 g) were collected preflight. Each subject was instructed to run at 6 mph for 3 min while ground reaction forces and high-speed video were collected. The treadmill was then bolted to the flight deck of a modified Boeing 727 aircraft leased by NASA from the Zero-Gravity Corporation (Arlington, VA).

Procedure

Of the approximately 42 parabolas carried out on each flight day, a subset of the parabolas were flown to achieve lunar and Martian gravity levels. When an aircraft is flown in a true Keplerian, or parabolic, trajectory, the net acceleration on the aircraft is briefly zero as the plane travels up and over the top of each parabola, resulting in a state of free-fall.[16] The period of reduced gravity typically lasts for approximately 20–25 s and is followed by a period of enhanced gravity as the plane "pulls out" of the descent on the back side of the parabola. However, the pilot can vary the trajectory flown such that the net acceleration is some nonzero value such as 0.17 g or 0.38 g, the accelerations on the Moon and Mars, respectively.

During the flights, subjects sat or lay down on the treadmill until the required gravity level was nearly achieved. Once the plane entered the initial stages of reduced gravity, spotters assisted the subject to a standing position astride the treadmill. When they were steady, the subjects mounted the treadmill and began running under the supervision of the spotters. GRF data were collected as subjects ran. Data collection and treadmill speed were terminated once the plane started to descend into the end of the parabola and gravity levels started to increase (**Fig. 1**).

Statistical Analysis

The component of GRF data normal to the treadmill surface was sampled at 1000 Hz and baseline corrected to zero force during the flight phase of running. Custom MATLAB functions detected key features of the curves so that contact time, flight time, and the magnitude of the first and second force peaks were detected. The first force peak (FP1) was defined as the peak, if present, in the first 20% of the contact phase. The second force peak (FP2) was the largest value in the entire contact phase, usually between 40–60% of the contact phase. The initial contact phases (~3–5 steps) while the subjects were still adapting to the treadmill movement were not used for analysis.

An average GRF curve in units of bodyweight in 1 g (BW) was calculated for each subject in each gravity condition. A time base of percent contact time was used for averaging. The number of cycles averaged for a given subject/condition was between 21–52 for reduced gravity conditions and up to 116 in 1 g (Table I). Contact time (CT: from foot-strike to toe-off) and flight time (FT: from toe-off to the next contralateral foot-strike) were calculated for each subject in each gravity condition. Stride length (SL: normalized by stature) was calculated as the product of treadmill speed and contact time divided by the subject's stature.

Repeated measures analysis of variance was performed in SPSS Version 23 (IBM Corp., Armonk, NY) to compare the various parameters under the three different gravity conditions. Since data for subject 3 in Martian gravity was missing, the average of data from all other subjects was used for this condition.

RESULTS

Gravity did not have a significant effect on contact time [$F(2,6) = 2.85$, $P = 0.092$]. There was a trend for CT to decrease with decreasing gravity {1 g: CT = 241.9 ms ± 3.4% [mean ± coefficient of variation (CV)], Martian: CT = 222.8 ms ± 8.5%, lunar: CT = 201.7 ms ± 15.1%}. Gravity had a significant effect on flight time [$F(2,6) = 16.76$, $P = 0.004$]. Flight time increased with decreasing gravity [1 g: FT = 102.6 ms ± 7.4%

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Fig. 1. Subject running on a treadmill during a lunar gravity parabola. Faces are blurred to protect privacy.

Gravity had a significant effect on FP1 [$F(2,6) = 231.1$, $P < 0.0001$] and FP2 [$F(2,6) = 548.8$, $P < 0.0001$]. Individual values for FP1 and FP2 under all gravity conditions are presented in **Table II**. FP1 and FP2 were found to decrease as gravity decreased [1 g: FP1 = 1.80 BW ± 9.0%, FP2 = 2.24 BW ± 11.7% (Mean ± CV); Martian: FP1 = 0.94 BW ± 22.3%, FP2 = 1.11 BW ± 15.2%; lunar: FP1 = 0.45 BW ± 40.9%, FP2 = 0.55 BW ± 32.6%; see **Fig. 3**]. FP1 and FP2 in all gravity conditions were significantly different from each other ($P < 0.001$ in all conditions), (1 g > Martian > lunar). These data were fit to a linear model expressing peak force as a function of gravity level. These equations are as follows:

(mean ± CV); Martian: FT = 210.9 ms ± 13.9%; lunar: FT = ms 322.3 ± 25.4%]. FT in both Martian and lunar gravities were significantly longer then FT in 1 g ($P < 0.0001$ and 0.01, respectively).

After a Greenhouse-Geisser correction of sphericity, there was a nonsignificant P-value for the effect of gravity on stride length [$F(2,6) = 4.79$, $P = 0.062$]. There was a trend toward longer SL in Martian gravity compared to 1 g ($P = 0.06$). Normalized stride length was 1.07 statures ± 6.0% (mean ± CV) in 1 g, 1.25 statures ± 7.0% in Martian gravity, and 1.52 statures ± 12.0% in lunar gravity. Three of the eight subjects (1, 7, and 8) showed marked increases in SL during lunar running while the remaining subjects showed only small changes (**Fig. 2**).

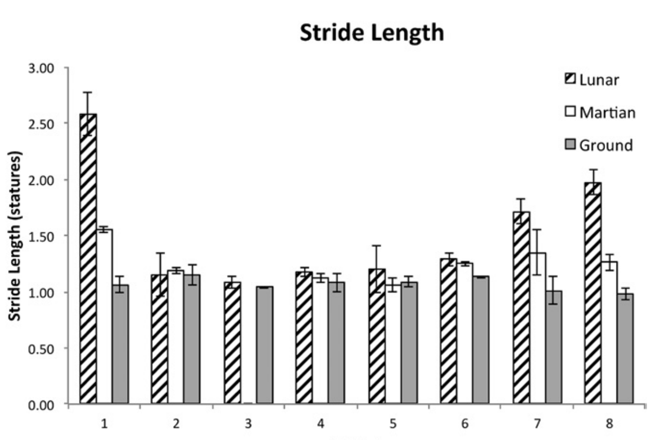

Fig. 2. Normalized stride lengths (in statures ± 1 CV) for all subjects running in each gravity condition (lunar = striped, Martian = white, 1 g = gray).

$$FP1 = 1.56x + 0.26 \quad (R^2 = 0.99) \qquad \text{Eq. 1}$$

$$FP2 = 1.96x + 0.29 \quad (R^2 = 0.99) \qquad \text{Eq. 2}$$

where FP1 and FP2 are in units of bodyweight and x is the gravity level as a fraction of 1 g.

Most subjects showed considerably greater within-trial variability in the patterns of GRF during lunar running compared to running in 1 g (e.g., mean FP2 CVs: 1 g = 11.7%, lunar = 32.6%; see Table II). An example of this variability is shown by a comparison of conditions in **Fig. 4**, where raw data taken from the subject who had most experience running in reduced gravity are shown in 1 g and lunar g, respectively.

The correlations between stride length and peak forces (FP1, FP2) in all gravity conditions were calculated and the R^2 values for these relationships are: FP1 vs. SL (0.02, 0.38, 0.004, in lunar, Martian, and 1 g, respectively), FP2 vs. SL (0.23, 0.05, 0.16 in lunar, Martian, and 1 g, respectively).

DISCUSSION

Aircraft flown in a parabolic trajectory present a challenging platform for human biomechanical experimentation. Subjects usually have little or no familiarity with the environment and the opportunities for acclimation are limited. It is, therefore, not surprising that there is considerable variability in the kinematics and kinetics of treadmill gait under such reduced gravity conditions. This variability was expressed in our experiment by increasing coefficients of variation in the peak GRFs as gravity decreased. However, it is likely that not all of the variability can be accounted for by the inexperience of the subjects. Increasing

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Table II. Mean Values (in Bodyweight ± 1 CV) of FP1 and FP2 for All Subjects in All Gravity Conditions Together with Overall Means.

	LUNAR				MARTIAN				GROUND			
SUBJECT #	FP1	FP1 CV	FP2	FP2 CV	FP1	FP1 CV	FP2	FP2 CV	FP1	FP1 CV	FP2	FP2 CV
1	0.49	34.8%	0.74	28.9%	1.18	20.2%	1.30	7.3%	1.85	12.1%	2.45	12.1%
2	0.30	35.1%	0.63	45.9%	0.41	19.5%	1.32	12.1%	1.72	5.7%	2.26	16.9%
3	0.49	38.1%	0.34	30.4%	Missing Data				1.81	7.6%	2.39	4.7%
4	0.42	38.6%	0.45	28.5%	0.82	16.1%	0.89	8.0%	1.82	8.2%	2.20	17.7%
5	0.32	63.1%	0.63	44.1%	0.77	58.9%	1.20	19.5%	1.58	10.3%	2.32	9.8%
6	0.64	27.8%	0.64	25.3%	1.09	17.1%	1.06	9.7%	1.99	5.9%	2.21	2.6%
7	0.66	37.7%	0.39	36.2%	1.47	10.9%	0.94	38.1%	2.10	10.1%	2.03	22.2%
8	0.31	51.9%	0.61	21.1%	0.84	13.6%	1.05	12.0%	1.55	11.8%	2.05	7.8%
Average	0.45	40.9%	0.55	32.6%	0.94	22.3%	1.11	15.2%	1.80	9.0%	2.24	11.7%

gravity may tend to "damp" the kinematics of gait, making it less likely that there will be extreme differences between adjacent strides. In contrast, when running in reduced gravity, it is not uncommon to temporarily lose equilibrium with an unusually strong push off which results in a higher flight path of the center of mass. Side to side stability is also affected and placement of the foot away from the midline of the treadmill is not uncommon.

Future studies may need to mitigate the within trial variability by providing their subjects with prolonged training to allow habituation to reduced gravity running such as that which would occur when astronauts exercise over a period of months in a lunar or Martian habitat. This would be expensive if the habituation were to be performed during parabolic flights, so a ground-based simulation of reduced gravity may be beneficial.[4,5,11]

Although there was a trend toward increased SL as gravity was reduced, the subjects were not homogenous in their responses. Three subjects showed marked increases in SL while the remaining five subjects showed only small increases. Despite these differences, the reduction in GRFs as ambient gravity decreased was common across all subjects and the R^2 for the relationships between SL and FP1, and SL and FP2 were generally poor. Thus, peak forces did not depend on chosen stride length. As expected, the peak forces decreased as gravity level decreased. The regression models (Eqs. 1 and 2) indicated that FP1 and FP2 decreased 0.156 BW and 0.196 BW, respectively, per 1/10 g change in ambient gravity.

There are several limitations to the current study that may have affected the findings. The sample size, as in most space-related studies, is small, and there are more women than men in our sample (6 women, 2 men). This is particularly relevant

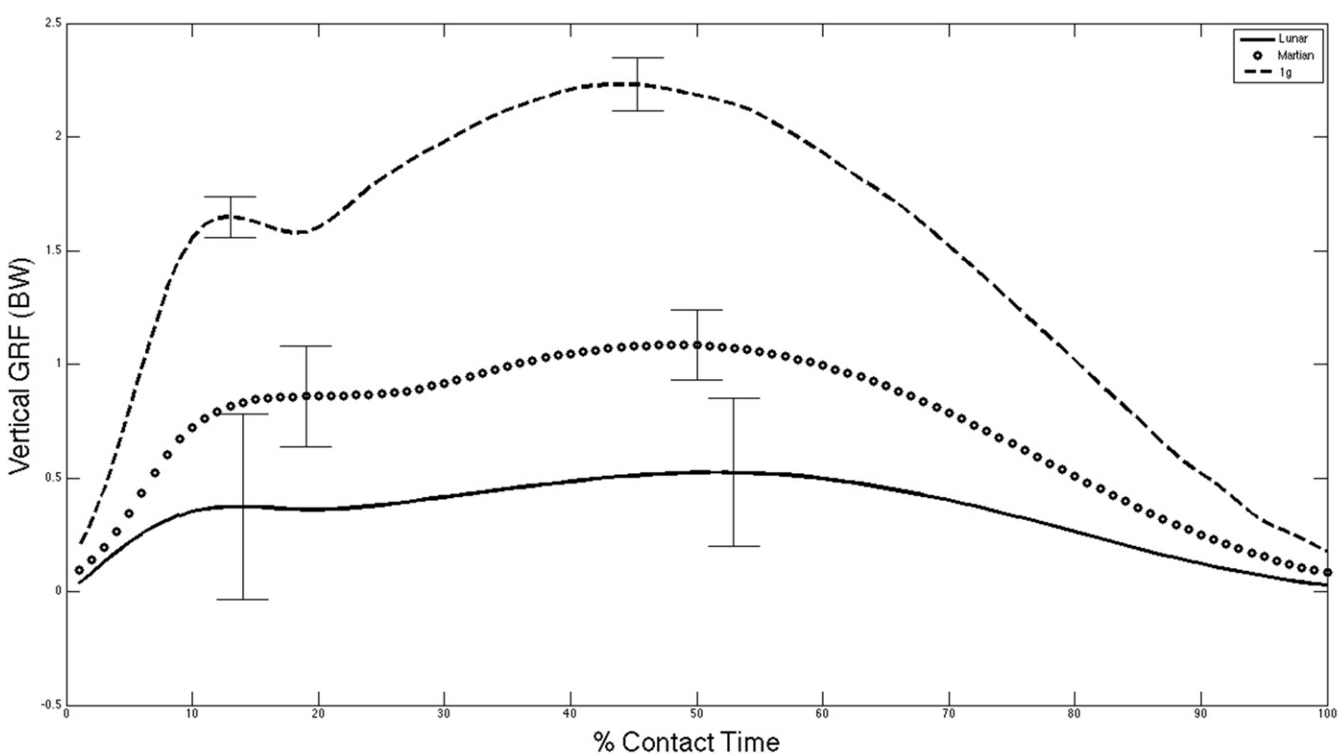

Fig. 3. Mean curves and coefficients of variation (CV) at FP1 and FP2 in the normal component of GRF for all subjects running in each gravity condition (lunar = solid, Martian = dotted, 1 g = dashed). Force units are normalized by bodyweight and the x-axis is 100% of contact time. Error bars are ± 1 CV.

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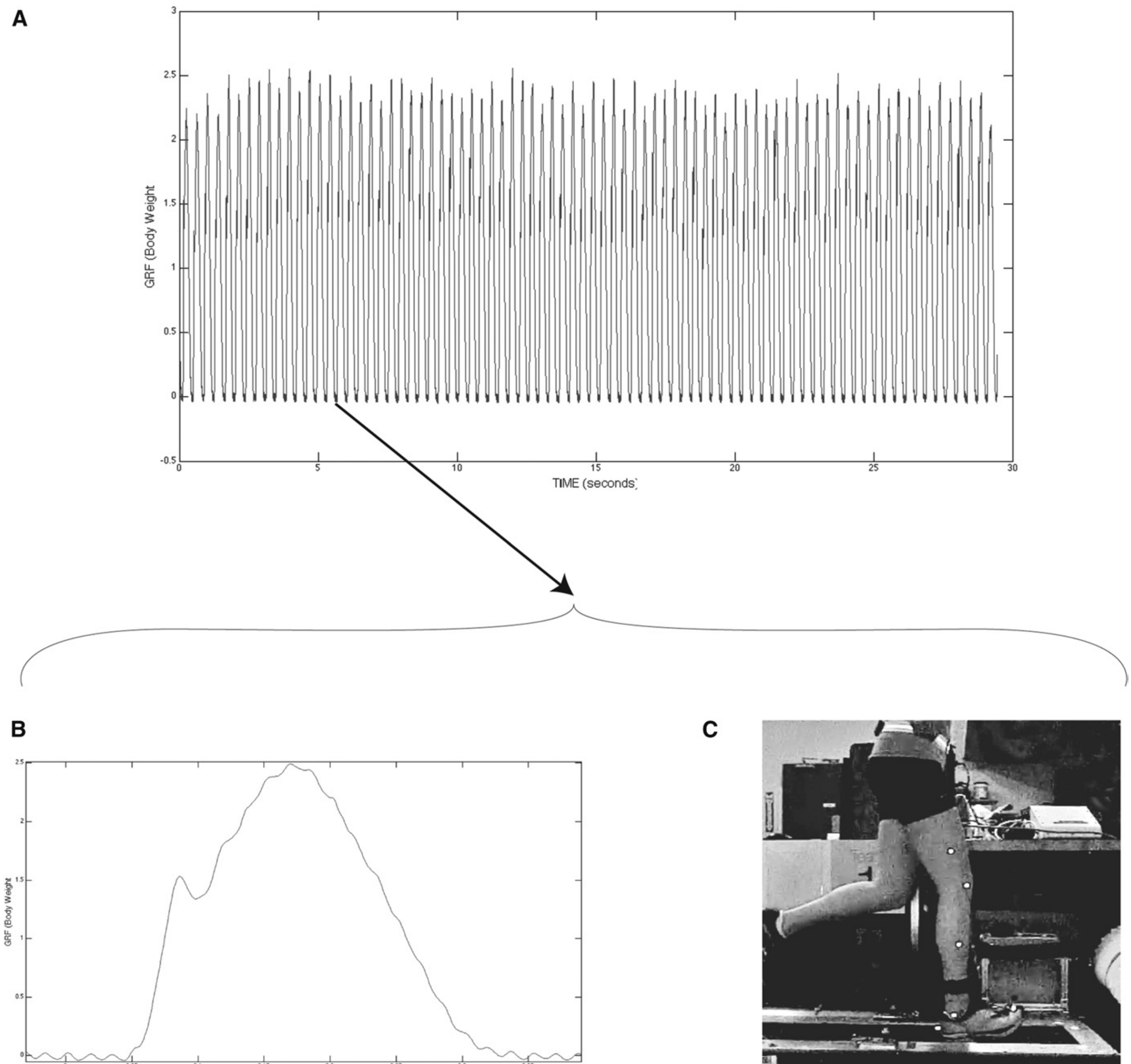

Fig. 4. A) Segment of the vertical ground reaction force vs. time curve for overground running. B) A typical single foot contact from A above. C) A single frame from a sagittal plane video in the region of footstrike. (Fig. continued on next page.)

because there appeared to be two distinct kinematic responses to reduced gravity (i.e., either a large or very small increase in stride length). It is notable that two of the subjects with marked changes were men. Our findings should be considered preliminary until a larger group of subjects can be studied. Future studies should explore if acclimation to reduced gravity running in a larger group of subjects identifies a primary pattern or if gender or stature is a significant factor. The length of the treadmill belt may also have been a significant factor in restricting stride length. The available "head room" above the treadmill was also limited by the height of the aircraft ceiling. Subjects may, therefore, have been hesitant to increase their vertical oscillation to the level that would be required for a "lunar lope" that was observed during lunar surface activity in Apollo missions[23] and in the early simulations of lunar running and loping.[15] Although we have "situational slow motion video" (not reported here), no formal measurements of joint kinematics were conducted. It should also be noted that only the vertical component of the GRF was measured and the antero-posterior and medio-lateral components may also contain useful information.[2] Finally, there may have been small deviations from the target lunar and Martian gravity values since trajectories are "hand flown" rather than programmed into an automatic flight control system. Treadmill mounted force plates have a much poorer frequency response than floor-mounted units. The first resonant frequency of our platform was determined by a hammer blow

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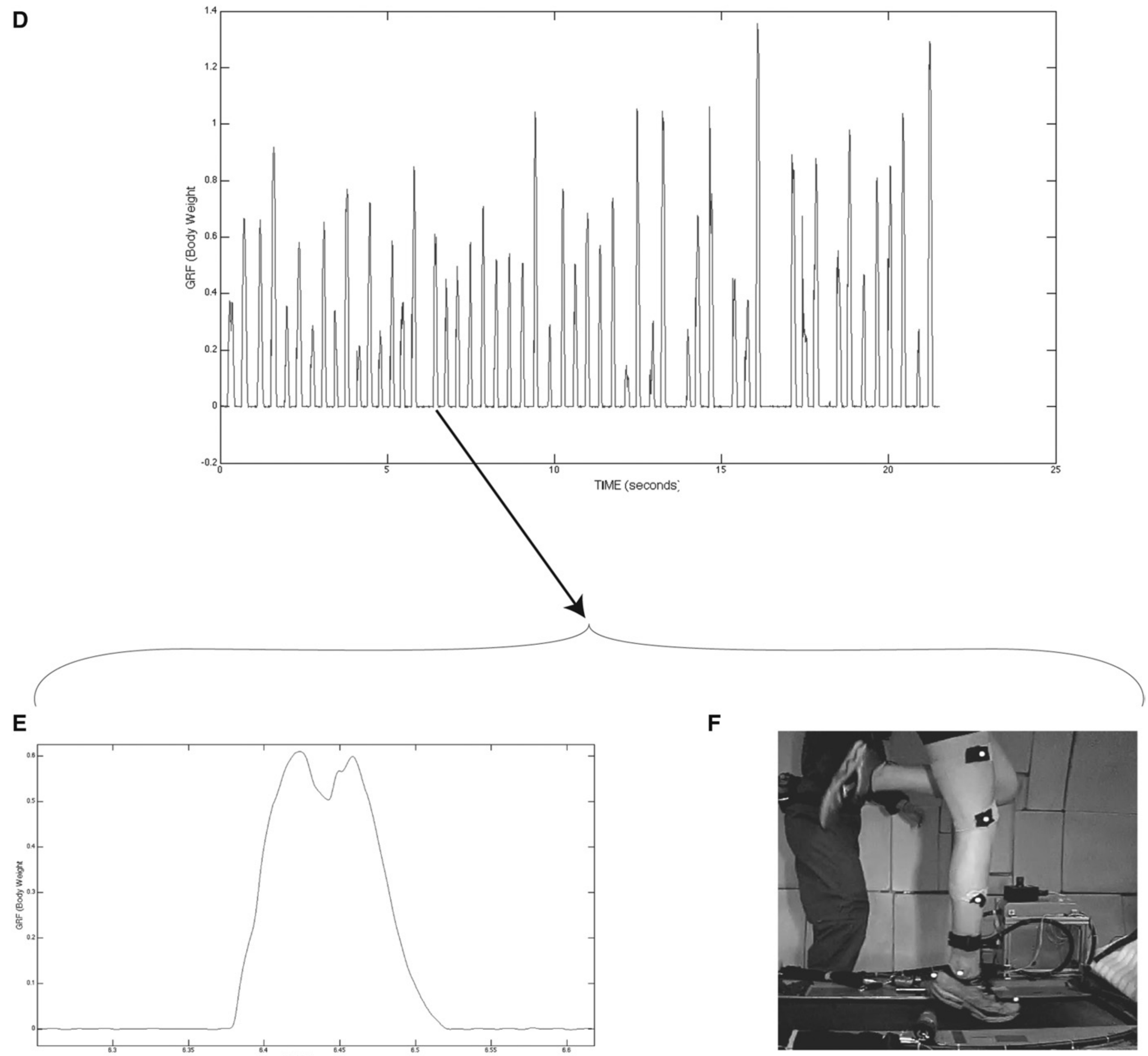

Fig. 4, Cont'd. D) Segment of the vertical ground reaction force vs. time curve for lunar running by the same subject as shown in A, B, and C who was an experienced lunar runner. E) A typical single foot contact from D above. F) A single frame from a sagittal plane video in the region of foot-strike. Note the instability in the vertical GRF pattern during lunar running compared to overground running. The variability is expressed by differences in the magnitude of the peaks, and by one or two extremely long flight phases during lunar running. Note that this subject does not display early first peak during lunar running in the majority of the contacts as would be expected from the extreme forefoot strike in lunar gravity.

to the platform while data were being sampled. The resulting oscillations in the signal over an approximately 1-s time period were determined to occur at an average frequency of 10 Hz. This is in contrast to values of 23 Hz and 35 Hz for other force-measuring treadmills and values of ~800 Hz in a floor-mounted force platform.[26] This poor frequency response must be considered in the interpretation of the data; however, it is the case at present that treadmills mounted on parabolic flight aircraft or space vehicles will have similar characteristics.

Within the stated limitations of the study, we conclude that unloaded treadmill running in lunar and Martian environments during exploration missions is not likely to be an osteo-protective exercise. Under simulated Martian conditions in this experiment, the peak forces were similar to those that we have previously observed during running with low harness loading on the International Space Station.[9] Similar foot forces were found by DeWitt and Ploutz-Snyder[6] during harness-loaded running on the International Space Station. In that setting, prior to the introduction of high-force resistance training and pharmacological intervention, crewmembers lost bone mineral density at important sites in the hip.[18] Extravehicular activity during lunar and Martian missions will certainly provide a portion of the

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loading required for maintenance of musculoskeletal health,[3] but will not likely be sufficient to fully mitigate bone[17,21,25] and muscle loss[8,19,27] that results from living in a reduced gravity environment. Loaded exercise will need to be performed[10] to enhance the countermeasure program to best protect bone and muscle strength and pharmacological intervention may be necessary.[20] If running is to be an exercise modality in a lunar or Martian habitat, it will require additional external loading, such as the use of subject load devices, to increase the GRFs to osteoprotective levels.[7,13,22]

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