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Biomechanical Evaluation of Locomotion on the Russian BD-1 Treadmill in a Weightless Environment (KC-135)

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Acronyms

0G	Zero Gravity (i.e. weightlessness; acceleration field = 0 m/s^2)
1G	Earth Gravity (i.e. acceleration field = **g** =9.807m/s^2)
EL	External Load
GRF	Ground Reaction Force
GTL	Heel to Greater Trochanter Length
HE	Harness Extender Strap Length Adjustment
ISS	International Space Station
PC	Personal Computer
RS	Restraint Strap
ROM	Range of Motion
SLD	Subject Loading Device
SPD	Subject Positioning Device

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ABSTRACT AND OPERATIONAL RELEVANCE

PURPOSE: We evaluated locomotion biomechanics on the BD-1 treadmill during exercise in weightlessness (0G) without a horizontal restraint strap (RS), and in normal gravity (1G) with and without a RS. **METHODS**: Eight subjects (5 men, 3 women, 33.3 ± 6.0 years, 174.3 ± 8.6 cm; 75.1 ± 11.7 kg) ran at 5, 8, and 14 km·h^{-1} during 0G onboard the KC-135 aircraft and in 1G. During 0G trials, the subjects were loaded using the BD-1 loading system and ran while gripping a stationary bar in front of their bodies with both hands. During 1G trials, subjects completed two conditions: gripping a stationary bar and using a RS. Treadmill speed, external load (EL; 0G only), gait timing parameters, vertical ground reaction forces (GRF), and kinematics data were collected. All statistical analyses were completed within each speed.

Results and Operational Relevance:

1) Subjects are able to attain speeds of 5 km·h^{-1} and 8 km·h^{-1} in 0G. This suggests that they may have difficulty obtaining sprinting speeds near and above 13 km·h^{-1} in 0G. It is unclear if the difficulty is due to individual subject characteristics, such as anaerobic fitness or leg strength, power, or endurance, or if it is due to the gravitational environment. **Recommendation**: *Speeds greater than 13* km·h^{-1} *should be prescribed with the advance knowledge that they may be difficult to attain and/or maintain.*

2) Mean total dynamic EL is approximately 520 N (116.9 lbs) and does not vary with locomotion speed. The EL for an individual is related to their heel to greater trochanter length (GTL) and the harness extender strap setting (HE). **Recommendation**: *The approximate EL can be found as: EL (in kg) = 24.43 + 0.45 × GTL (in cm) – 0.38×HE (in cm).*

3) Contact time and cadence do not differ between 0G and in 1G with or without the RS. Contact times were similar to those found during earlier motorized treadmill evaluations, but cadences appeared to be greater. Peak vertical GRF and impulse also do not differ within speeds between 0G and in 1G with or without the RS. Vertical GRF trajectories reveal the absence of an impact peak, suggesting that the foot has already begun to move rearward prior to heel strike. Peak GRF appears to be greater at each speed as compared to similar speeds on a motorized treadmill, but impulses are similar. **Recommendation**: *Subjects will generate greater peak forces on the BD-1, probably due to the need to propel the treadmill. Exercise prescription should take increased use of the hip and knee musculature into account during BD-1 exercise.*

4) Subjects appear to perform gait with an increased forward lean, minimal hip extension, 50-90 degrees of knee flexion, and varying ranges of ankle flexion. Range of motion (ROM) at each joint was not affected by gravitational or RS condition, but there were differences in trends between subjects. Hip ROM remains similar but knee ROM appears to increase and ankle ROM appears to decrease as locomotion speed increases. **Recommendation**: *When prescribing exercise onboard ISS, hip extensor range of motion should be addressed. In addition, when utilizing locomotor exercise at higher speeds, ankle flexor/extensor exercises should be used to supplement the possible reduced use of this musculature.*

GOAL

The purpose of this investigation was to evaluate locomotion on the Russian BD-1 non-motorized treadmill under three conditions: weightlessness (0G) without a simulated subject positioning device, or horizontal restraint strap (RS), normal gravity (1G) without a RS, and 1G with a RS. Various outcome measures were evaluated, including the applied external load (EL), vertical ground reaction force (GRF), the ability to achieve specific locomotion speeds, and joint kinematics. The goal of this research was to better understand how locomotion and the related forces experienced by the musculoskeletal system during non-motorized treadmill locomotion in 0G compare to locomotion on the same device in 1G.

INTRODUCTION

Long-term exposure to microgravity has been shown to result in physiological detriments to the musculoskeletal system, including bone loss in weight-bearing areas including the calcaneus, tibia, proximal femur, and pelvis (Schneider et al., 1995; LeBlanc et al., 2000). While the specific stimulus for bone maintenance remains unclear, it has been shown that bone responds to mechanical loading (Cullen et al., 2000; Mosley & Lanyon, 1998; Mosley et al., 1997). Research has shown that exercise which results in mechanical loading may be of benefit in stimulating bone growth (Judex & Zernicke, 2000; Heinonen et al., 1996).

A treadmill is used onboard the International Space Station (ISS) to allow impact-loading exercise. During locomotion in weightlessness, crewmembers wear a harness and tether in order to maintain contact with the treadmill. The tether provides an external load (EL) that pulls the crewmember back towards the treadmill, creating impact-loading between the treadmill and foot. The amount of EL is adjustable and can be determined by the crewmember. Due to possible breakdowns of the treadmill, and owing to the criticality of this mode of exercise, the Russian designed BD-1 treadmill is a contingency device.

The BD-1 treadmill (see Figure 1) is a non-motorized device and was the focus of this investigation. The device consists of a vinyl belt that moves over a series of metal rollers. The tread surface area is 82 cm long by 37 cm wide. The treadmill is non-motorized, requiring the subject to provide the power necessary to move the tread. The requirement for the subject to propel the belt may result in an increased amount of forward lean in order to aid in the generation of rearward forces by the foot and leg (Gamble, 1988; Lakomy, 1987). A subject positioning device (SPD) may aid in reducing forward lean because of the rearward force it places at the subject's waist. The EL applied to the crewmembers during exercise on the BD-1 is only slightly adjustable because the bungee system built into the device provides a low relative extension during locomotion. Past investigations have demonstrated that the EL provided by other loading systems varies substantially during motorized treadmill exercise in 0G (Schaffner et al., 2005). It is unknown how the non-motorized treadmill will affect EL and locomotion kinetics and kinematics.

Figure 1. The BD-1 treadmill. The padded frame surrounding the subject was used for safety purposes and to provide a handrail that subjects could push against; it is not a part of the treadmill.

We have collected some data on locomotion kinematics and kinetics in weightlessness (DeWitt et al., 2004; Schaffner et al., 2004; DeWitt et al., 2003). These studies were conducted using a motorized treadmill on which the required gait patterns may be different than on a non-motorized treadmill. Cavanagh et al, (1987) and Thornton et al., (1997) presented kinematic data collected during non-motorized treadmill locomotion in weightlessness during STS-7 and STS-8. Although their dataset is small, joint kinematics are presented that serve as a reference for this study. There have been no reported data on the forces necessary to drive a non-motorized treadmill.

Because of the lack of quantitative data concerning locomotion biomechanics on a non-motorized treadmill, the purpose of this study was to quantify EL levels and locomotion parameters on the BD-1 in 0G and in 1G. The secondary purpose was to assess the use of the RS upon locomotion biomechanics during 1G exercise. Quantification of these parameters are beneficial to understanding how long term use of the device may affect the human body, and will help to create more suitable exercise prescriptions for crewmembers during extended spaceflight.

HYPOTHESES

1) The ability to achieve specific locomotion speeds will not be affected by gravitational or RS condition.
2) The dynamic EL during locomotion in 0G will be affected by subject anthropometrics.
3) The peak vertical GRF produced will be different in 0G compared to 1G for either RS configuration at the same absolute speeds.
4) Gait parameters and locomotion kinematics, including contact time, cadence, joint displacements and velocities, and forward lean will be different in 0G compared to 1G for either RS configuration at the same absolute speeds.

METHODS AND MATERIALS

Eight subjects (5 men, 3 women, 33.3 ± 6.0 years, 174.3 ± 8.6 cm; 75.1 ± 11.7 kg, mean±SD) ran at 5, 8, and 14 $km \cdot h^{-1}$ during weightlessness (0G) onboard the KC-135 aircraft (see Figure 2) and in normal gravity on the ground (1G). Subjects were free from injuries and pathological conditions which could potentially affect the results of the study. Prior to participation, all subjects signed an informed consent document. This study was approved by the Johnson Space Center Committee for the Protection of Human Subjects.

Figure 2. BD-1 treadmill evaluation experiment being performed on NASA KC-135 Research Aircraft.

All 0G trials occurred onboard the NASA KC-135 aircraft. The KC-135 flies in a parabolic trajectory that allows for approximately 20 seconds of reduced gravity, followed by approximately 50 seconds of non-zero gravity. Each flight consists of approximately 40 parabolas performed in multiple sets. During this investigation, data were collected over four separate flights, with two subjects tested during each flight. All 1G trials occurred in the Exercise Physiology Laboratory at Johnson Space Center. For both airborne and ground trials, the treadmill was surrounded in the front and sides by a padded steel safety frame. The frame offered protection against the subject falling after a stumble and also provided a handrail for the subjects to push against in the non-RS trials.

Prior to any data collection, each subject participated in a familiarization session in the laboratory. Each subject ran and walked at freely chosen speeds to become accustomed to the treadmill. Next, each subject completed a series of seven running trials to allow familiarization with the approximate time of exercise and rest onboard the aircraft. During these trials, the subjects ran for 20 seconds and rested for 50 seconds during multiple 5, 8, and 14 $km \cdot h^{-1}$ locomotive bouts. These times correspond to the 0G and non-0G times on the KC-135 as found through past experience.

Belt motion and locomotion on the BD-1 occurs solely due to the forces provided by the subject. Within the BD-1, there is an internal resistance to the motion of the belt that can be set by the user. For this investigation, the belt resistance was set at the lowest setting possible. Pilot testing revealed that the belt resistance was approximately 137 newtons (N).

Because the internal resistance of the treadmill belt was not zero, a forward-directed reaction force will be applied to the subject by the treadmill. A rearward-directed force must also be applied to the subject to counteract the fore-aft ground reaction force, otherwise the subject will be propelled forward. During 0G and 1G trials, the subjects placed their hands on the front upper bar of the treadmill safety frame to create this rearward-directed reaction force. In addition, the subjects completed an additional condition during 1G trials using a horizontal restraint strap (RS). During the RS trials, the rearward-directed force was applied to the subjects using extender straps attached horizontally between the rear of the safety frame and the Russian harness worn by the subjects. These trials were used to simulate the SPD onboard ISS.

EL during 0G trials was applied to each subject by the bungee loading system built into the treadmill. The BD-1 was designed with a long bungee that winds around pulleys on the lower front and rear of the device. The bungee applied load to the subjects through a waist and shoulder harness, and was attached to the right and left side of the belt with adjustable extender straps that clipped to the metal terminations at each end of the bungee. The applied EL can be distributed between the waist and shoulders by adjusting the length of the harness shoulder straps. The EL can also be varied slightly by adjusting the length of the extender straps. Each subject was outfitted prior to data collection with each harness in a configuration that was deemed comfortable. The load provided to the subjects was not standardized as a percentage of body weight because the range of adjustability of the bungee and extender straps could not accommodate the differences in subject anthropometrics. Also, the load distribution between the shoulders and waist was not standardized because there were no means to measure these load components independently. The harness was worn during 0G and 1G trials with the RS; during 1G trials without the PH, no harness was worn.

Data were collected using specialized instrumentation systems during each trial. EL was measured using load cells interfaced with a PC. Treadmill speed was recorded with a digital speedometer interfaced with a PC. Ground reaction forces were measured with pressure insoles. Running kinematics were evaluated with a motion capture system. Each system and its parameters will be discussed in greater detail in the following sections. The treadmill speed, load cells, and ground reaction force data were synchronized during collection. The motion capture system was not synchronized with the other devices.

External Load, Bungee Extension and Treadmill Speed Measurement

The EL applied to each subject was measured at 120 Hz using load cells (Entran, Inc., Fairfield, NJ). The load cells were placed between the harness extender strap attachment and the loading bungee on both sides of the subject to allow for external load measurement on both sides of the subject (see Figure 3). Displacement transducers mounted on the right and left side of the subject (Ergotest Technology, Langesund, Norway and Ametek Rayelco PV-80A, Costa Mesa, CA, respectively) were used to measure the linear displacement of the load attachment points at the subjects harness (bungee system extension). Two loading configurations were tested, a low load and high load. The low load condition consisted of the load cells inline with the harness extender straps at their longest setting. This provided the minimum bungee extension and thus the lowest loading for a given subject. In the high load condition, the load cells were removed (since the length they take up in the attachment scheme reduces the bungee extension) and the extender straps were moved to their shortest lengths. Unfortunately, this meant that the bungee load could not be measured directly during locomotion. To make up for this, a bungee loading curve characterization was performed prior to any exercise sessions. The two ends of the bungee were extended simultaneously, starting at 10 cm and increasing to 55 cm in increments of 5 cm. At each extension, the bungee tension was measured at each end using the load cell system. The total load was calculated by adding the two load cell measurements together. Two trials were performed and the results were averaged.

Figure 3. Close-up of connection between harness and loading bungee illustrating load cell orientation during data collection.

The BD-1 was built with an internal digital speed sensor. When the belt was in motion, the speed sensor output was a 3-volt peak-to-peak square wave signal where the frequency of the square wave was a function of belt speed. The speed was recorded at approximately 4 Hz and displayed on a notebook computer (Compaq, Houston, TX) placed in front of the subject.

A data acquisition system, equipped with LabVIEW programming software (National Instruments, Austin, TX), was interfaced to the speed sensor and load cells. The customized LabVIEW software was used to capture and condition load cell data at a cutoff frequency of 4 Hz with a Butterworth low-pass filter and to convert the frequency of the speed sensor signal to a numeric speed.

Ground Reaction Force

Vertical GRF data were measured during all trials using pressure sensing insoles (Tekscan, Inc., S. Boston, MA). Each subject had their own pair of custom-fitted insoles that were placed between the insole of the shoes and their feet. During each condition, the insoles were calibrated to the subject's body weight prior to any data collection. Pressure data from the sensors within each insole were recorded by a data collection PC. A spotter ensured that the sensor wires that connected each insole to the PC did not interfere with the normal gait of the subject. Data were collected at 250 Hz for 15 sec. Data collection for the pressure insoles, treadmill speed, and load cells were initiated simultaneously with the same button-press trigger. GRF parameters (peak force, and impulse) were determined using custom software. Multiple footfalls from each foot were analyzed individually to ensure that outcome variables were computed accurately. Any partial footfall measurements were eliminated from the analysis. Trial means were then computed for each outcome variable using data from all of the footsteps for the entire trial.

Gait Parameters

Gait parameter outcome variables of interest included contact time and cadence and were obtained using the timing measures from the pressure insoles. Contact time was defined as the duration, in seconds, that the foot was in contact with the treadmill during a footfall. Initial contact was defined as the instant that the GRF rose above 10 N; toe-off, or the instance the foot left the ground, was defined as the instant that the GRF fell below 10 N. Stride time was defined as the duration between successive heel strikes of the same foot. Cadence was defined as the amount of strides that the subject took per second, and was computed as the inverse of stride time.

Kinematics

Kinematic data were collected with a six-camera infra-red video motion capture system (eMotion, Inc., Milan, Italy). Reflective markers were placed on the right side of the subject during 0G trials and left side of the subject during 1G trials with the assumption that leg motion was symmetrical. Markers were placed to approximate the joint centers of the shoulder, hip, knee, ankle, and top of the foot at the base of the third metatarsal. An additional marker was placed on the anterior-lateral thigh arbitrarily so it did not lie on the axis connecting the knee center to the hip center (see Figure 4). During 0G trials, the hip joint center was often obscured by the harness and EL connection. Therefore, an additional marker was placed on the lateral-rear of the waist belt. 3-D position data were collected at 120 Hz. Prior to any data collection, the activity volume was calibrated to within 1 mm of re-prediction accuracy. After calibration, but prior to any running trials, a trial was collected while the subject stood still to define the marker orientation associated with each joint in the neutral position.

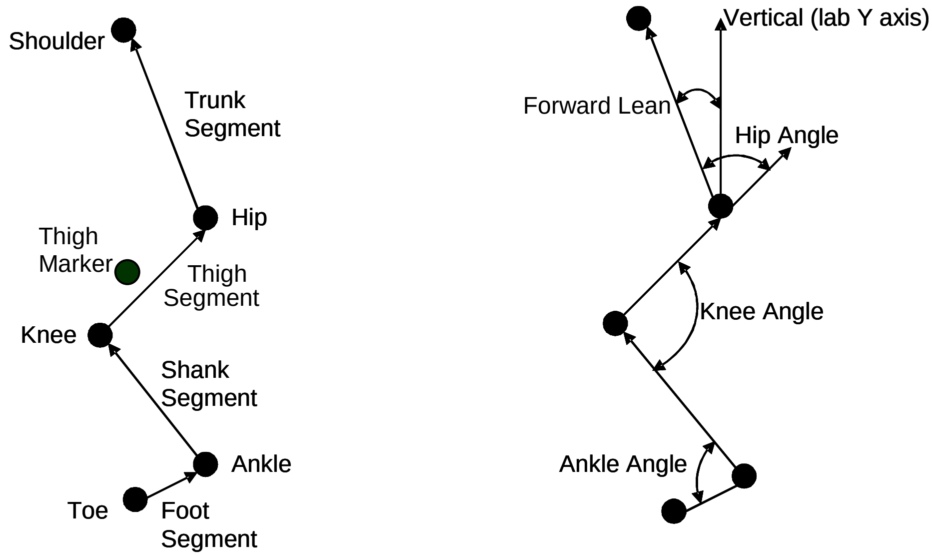


Figure 4. Marker positions and joint angle definitions used during the kinematics analysis.

Multiple strides from two trials at each speed were analyzed for each subject. Marker position data were filtered using a 4^{th} order Butterworth low pass filter with cutoff frequencies ranging from 2-8 Hz as determined after a power analysis of the raw signal data. The markers allowed the body to be modeled as 4 rigid segments: trunk, thigh, shank and foot. Each segment was approximated as the vector connecting the distal to proximal joint centers at the segment endpoints. However, for 0G trials, the thigh was modeled as the vector connecting the knee to the thigh marker due to the absence of the hip marker. Forward lean was defined as the angle separating the trunk from the vertical axis of the lab reference frame using the average position of the shoulder as the endpoint of the trunk vector. Using the shoulder average position was required because some shoulder motion occurred due to rotation of the trunk, which would not be indicative of forward lean. Hip angle was defined as the angle separating the trunk and thigh. Knee angle was quantified as the angle separating thigh and shank. Ankle angle was defined as the angle between the shank and foot.

It was assumed that any motion outside of the sagittal plane was negligible. Therefore, the angles of interest were computed as absolute angles separating the adjacent segments. Once joint angles were computed, they were adjusted using data obtained during the quiet standing trial to account for the offsets related to the neutral positions of each joint. Positive knee and hip angle values reflect flexion and positive ankle angles reflect plantarflexion. Angular velocity was calculated using finite central differences. Positive angular velocities indicate flexor movement, while negative angular velocities indicate extensor movement.

Outcome Variables and Statistical Analysis

During 1G data collection, subjects completed two trials at each speed at each condition (RS vs. no PH) resulting in 12 (2 × 3 × 2) trials per subject. During 0G trials, subjects completed 2-4 trials at each speed. The numbers of trials per subject used during the 0G analysis varied and are addressed in the results. There were several outcome variables of interest in this investigation. Each variable and the statistical analysis utilized are described in the following paragraphs. For all statistical tests, an alpha of $p<.05$ was used to determine significance.

1. Treadmill Speed: The mean and standard deviation of the treadmill speed for all trials were computed to determine if the subjects were able to achieve the desired speeds of 5, 8, and 14 $km \cdot h^{-1}$. An ANOVA with trial type (0G, 1G without the PH, and 1G with the PH) was used for each speed to determine if there were any differences in locomotion speeds between conditions.
2. External Load: The mean and standard deviation of the EL experienced by each subject was computed for each 0G trial. An ANOVA was used to determine if there were effects of running speed upon the EL. In addition, subject by subject results were examined using forward stepwise multiple regression to determine if EL was related to the subject heel to greater trochanter length and body weight.
3. Kinetic and Gait Parameter Variables: Peak force and impulse were computed for each footfall of each trial. In addition, contact time and cadence were also computed using the footfall data. Each of the outcome variables were then examined within each speed using an ANOVA with repeated measures to determine any significant differences between conditions. Any significant interactions were examined with Tukey-Kramer post hoc t-tests.
4. Kinematic Variables: For each joint angle, the maximum, minimum, and range of motion were computed for multiple strides of each trial. In addition, the peak extension (positive) and flexion (negative) velocities were computed for each stride. The mean of each of these measures was then computed for each trial. An ANOVA with repeated measures was used to compare the locomotion conditions within each speed for each variable except forward lean. The loss of the hip marker during the 0G trials resulted in data only being available for the 1G condition. Therefore, a paired t-test was used to compare RS conditions within speeds.

RESULTS

Locomotion Speed

Subjects completed multiple trials at the target speeds of 5, 8, and 14 $km \cdot h^{-1}$. One subject was unable to complete the 1G trials at 14 $km \cdot h^{-1}$, so that subject was eliminated from the analysis for that speed. Table 1 reveals that the subjects ran similarly during all conditions except for the 14 $km \cdot h^{-1}$ conditions. Examination of the data suggests that at 5 $km \cdot h^{-1}$ and 8 $km \cdot h^{-1}$, the subjects were able to attain and maintain the desired speeds. At the fastest condition in 0G, however, the subjects had difficulty attaining a mean speed of 14 $km \cdot h^{-1}$. The 14 $km \cdot h^{-1}$ trials in 0G were different than those in 1G using the simulated PH.

Table 1. Mean (SD) velocities obtained on the BD-1 during locomotion in 0G and 1G.

	0G	1G	
Desired Speed (km·h^{-1})	**No RS**	**No RS**	**RS**
5	5.05 (0.16)	5.06 (0.18)	5.27 (0.25)
8	7.81 (0.33)	8.16 (0.13)	8.28 (0.14)
14	13.03 (0.60)	13.73 (0.72)	14.43 (0.54)*

* Significantly different than 0G (p<.05)

Load and Displacement

Mean Total External Load

The bungee load versus extension calibration curve is shown in Figure 5. The two lower curves depict the load and extension measured from each side. The close correspondence of the two curves indicates that the load is well balanced on each side, a feature inherent in the single bungee design (as opposed to using a separate bungee on each side). The total load curve is highly linear, as indicated by the high r-squared value (0.99). The slope of the regression line, 3.717 N/cm, represents the stiffness of the bungee loading system.

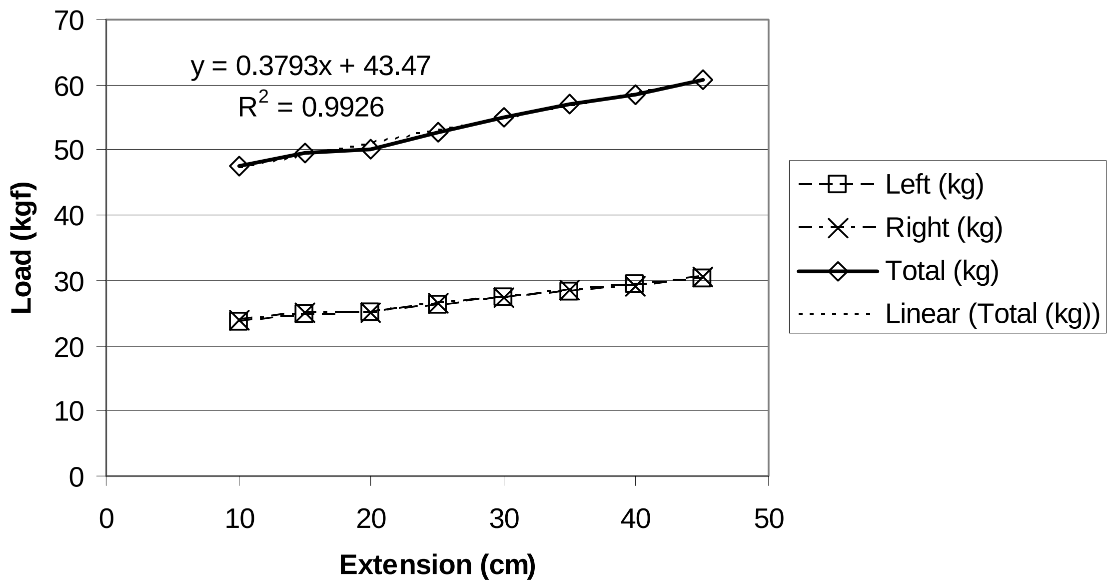


Figure 5. Bungee load versus extension calibration curve. The lower curves represent the load and extension measured on each side. The upper curve is the sum of these two curves, representing the overall bungee system load versus extension curve.

Mean Total External Load

EL was measured during 64 trials across seven subjects during 0G locomotion (for one subject the load cells failed). The mean total EL was computed as the sum of the mean load for the entire trial of the right and left load cells. Means are expressed in kilograms and in % BW (see

Table 2). There were no significant differences found between speed conditions, suggesting that locomotion speed does not affect the mean EL experienced by each subject.

Table 2. Mean (SD) total load expressed in kg and %BW for each speed during BD-1 locomotion in 0G

	Speed ($km \cdot h^{-1}$)		
	5	8	14
Total Load (kg)	53.44 (2.20)	52.77 (2.14)	52.35 (2.06)
Total Load (%BW)	0.71 (0.09)	0.70 (0.09)	0.70 (0.09)

While the relatively small standard deviation for each measure indicates that the mean EL remains consistent across subjects, it was also of interest to see if stature affects the mean EL. Table 3 lists the subject by subject mean total loads in kg and %BW for all trials. In addition, each subject's BW and heel to greater trochanter length (GTL) are shown. Pearson product moment correlations revealed that mean EL expressed in % BW was significantly correlated with GTL and BW (see Table 4).

Table 3. Mean (SD) total load and anthropometric measurements for each subject

Subject	BW (kg)	GTL (cm)	Mean EL (kg)	Mean EL (%BW)
3	60.00	84	49.34 (0.87)	0.82 (0.01)
1	63.64	85	51.65 (0.32)	0.81 (0.01)
4	76.36	91	51.20 (1.03)	0.67 (0.01)
6	81.82	92	53.15 (0.38)	0.65 (0.01)
7	75.00	92	54.35 (1.03)	0.72 (0.01)
5	95.00	93	54.16 (0.57)	0.57 (0.01)
2	80.91	95.5	55.52 (0.45)	0.69 (0.01)

Table 4. Correlation coefficients relating subject anthropometrics to mean external load

	Mean Load (kg)
BW	0.70*
GTL	0.85*

* Significantly correlated ($p<.05$)

A post hoc stepwise multiple regression using body weight and GTL as inputs to predict mean total load (low load configuration) in kg was executed and it was found that the mean EL could be predicted using GTL (See Figure 6). Adding BW to the equation did not improve the prediction level. The EL for the high load configuration could not be measured directly since the load cells were not connected (to avoid decreasing the load). However the bungee load calibration curve (Figure 5) provides a means of estimating the high load based on the low load measurement. The change in bungee extension provided by the load cell removal and shortening of the harness extender straps was 32.4 cm. Multiplying this by the bungee system stiffness of 3.72 N/cm gives a load change of 12.3 kg. Since the additional bungee extension was the same regardless of subject size, the change in load was the same for all subjects. By adding this load change to the linear regression line for the low load, the high load can be estimated (Figure 6). Thus, the overall range of loading available to all subjects was approximately 49.9 kg to 67.4 kg. The equation provided in the figure caption represents the case where the load cell is placed in line with the harness and the harness extender strap is on its longest setting. Removing the load cell and setting the harness extender strap on its shortest setting would increase the EL by 12.3 kg. Also, if we account for harness extender strap length adjustment (HE), the equation becomes:

$$EL\ (kg) = 24.43 + 0.45 \times GTL\ (cm) - 0.38 \times HE\ (cm),$$

where HE = 0 cm (shortest adjustment) to 14.9 cm (longest adjustment).

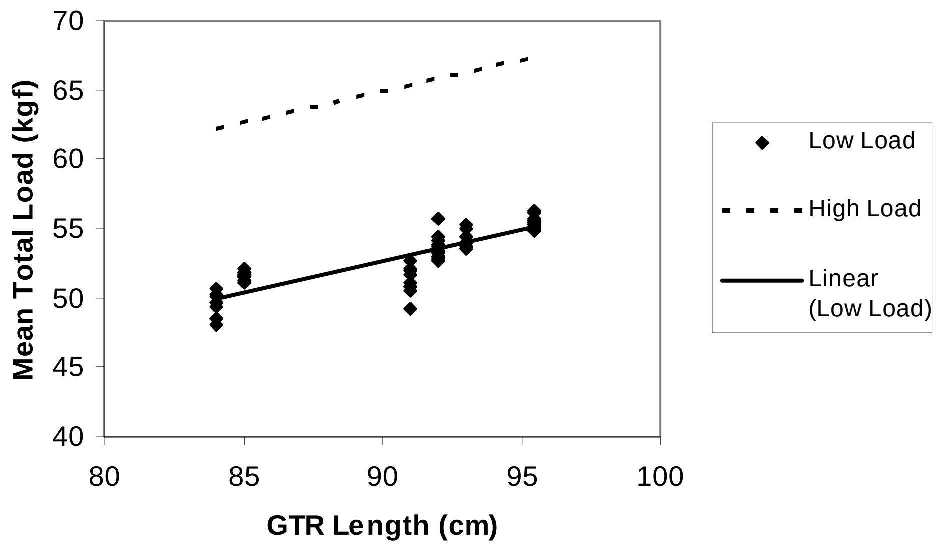


Figure 6. Scatter plot of external load vs. greater trochanter length. EL (kg) = 12.13 +.45 × GTL (cm); r^2=.72 (low load)

Gait Parameters and Ground Reaction Force

Prior to any statistical analyses and after data processing, the dataset was examined subject by subject to determine if any outliers existed. A total of 5111 footfalls were analyzed from 168 trials. There were trials during which data were not collected due to hardware malfunction. The complete subject trial means for contact time and peak GRF are shown in the Appendix.

It was found that for one subject (5), no data were collected during the 0G trials. The dataset for that subject was therefore eliminated from the analysis. For another subject (6), the 0G peak GRF values were consistent, but much lower than those exhibited by the other subjects. It was assumed, therefore, that some calibration error may have occurred that resulted in erroneous data for that subject, so that subject was also eliminated from the analysis. Finally, a subject (1) could not complete the 14 $km \cdot h^{-1}$ trials in 1G, and the 0G data for the 8 $km \cdot h^{-1}$ trial were not recorded. This subject was only kept for the 5 $km \cdot h^{-1}$ trials. This resulted in a total of 3963 footfalls from

133 trials being used from 6 subjects in the 5 km·h^{-1} analysis, and 5 subjects in the 8 and 14 km·h^{-1} analysis.

Trial Analysis

Student's t-tests were executed within each speed comparing each outcome variable during 0G between trials with and without the load cell placed inline with the bungees. No significant differences were found between the load cell conditions. Therefore, all data were grouped, regardless of load cell condition, for the subsequent analyses of gait and GRF parameters.

Contact Time and Cadence

There were no significant differences in contact time or cadences between locomotion conditions within each speed (see Table 5). It appears that contact times tended to decrease while cadences tended to increase as speed increased during BD-1 locomotion.

Table 5. Mean (SD) contact times and cadences during locomotion on the BD-1 in 0G and 1G

		0G	1G	
Desired Speed (km·h^{-1})		**No RS**	**No RS**	**RS**
5	**Contact Time (s)**	0.57 (0.04)	0.57 (0.03)	0.56 (0.06)
	Cadence (Strides·s^{-1})	1.08 (0.06)	1.07 (0.06)	1.11 (0.10)
8	**Contact Time (s)**	0.35 (0.05)	0.33 (0.01)	0.33 (0.03)
	Cadence (Strides·s^{-1})	1.42 (0.05)	1.50 (0.04)	1.49 (0.11)
14	**Contact Time (s)**	0.24 (0.03)	0.23 (0.01)	0.23 (0.02)
	Cadence (Strides·s^{-1})	1.61 (0.12)	1.71 (0.11)	1.71 (0.17)

Typical GRF Trajectories

Typical GRF trajectories are illustrated in Figure 7 – Figure 9. The trajectories for 5 km·h^{-1} are very similar to normal overground walking (Munro et al., 1987). The characteristic shape of two peaks are apparent, with the first peak occurring as the weight is applied to the heel during foot-ground contact, and the second peak occurring as the subject propels the belt backward.

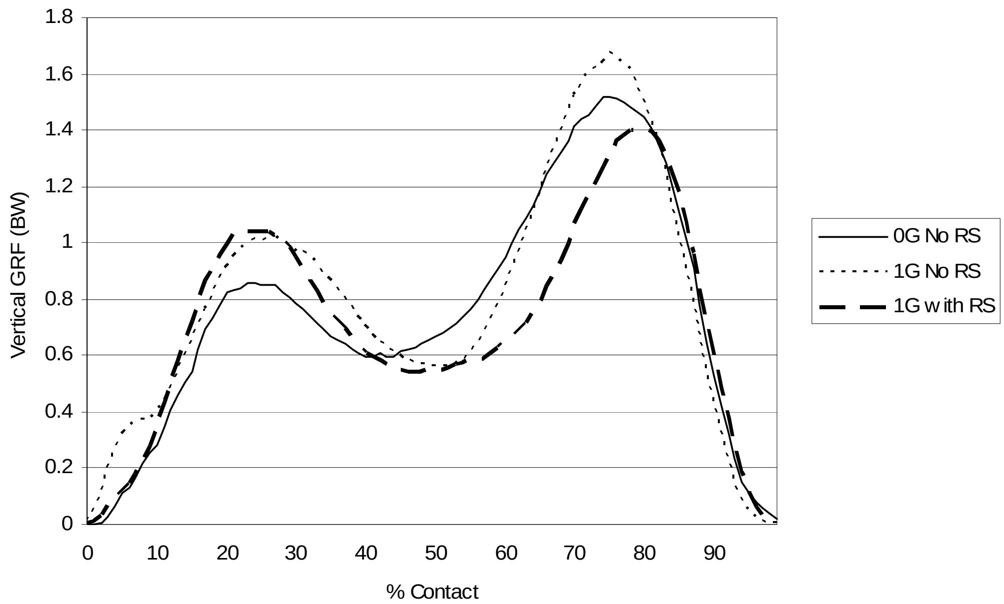


Figure 7. Typical vertical GRF trajectory during 5 km·h^{-1} locomotion in 0G and 1G on BD-1.

The GRF trajectories during 8 and 14 km·h^{-1} speeds are similar to each other in that a single peak is exhibited. The lack of an initial peak suggests that the heel strike that normally occurs during overground and motorized treadmill locomotion is not apparent during running on the BD-1. The single peak represents the peak force generated to propel the treadmill belt during the footfall. It should be noted that the GRF measured was in the vertical direction. It was not possible to measure any forces parallel with the treadmill surface.

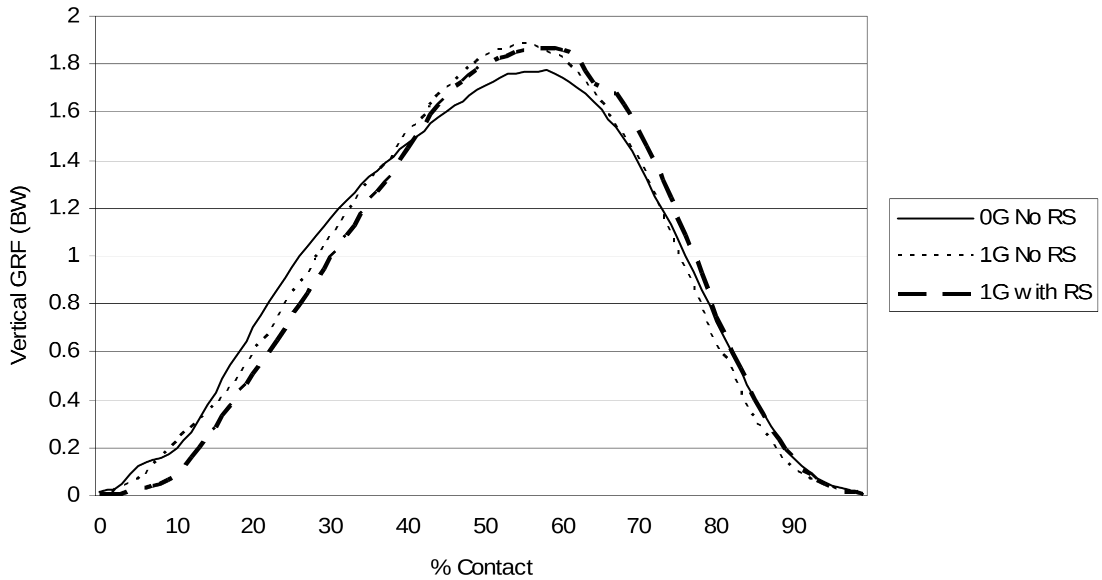


Figure 8. Typical vertical GRF trajectory during 8 km·h^{-1} locomotion in 0G and 1G on BD-1.

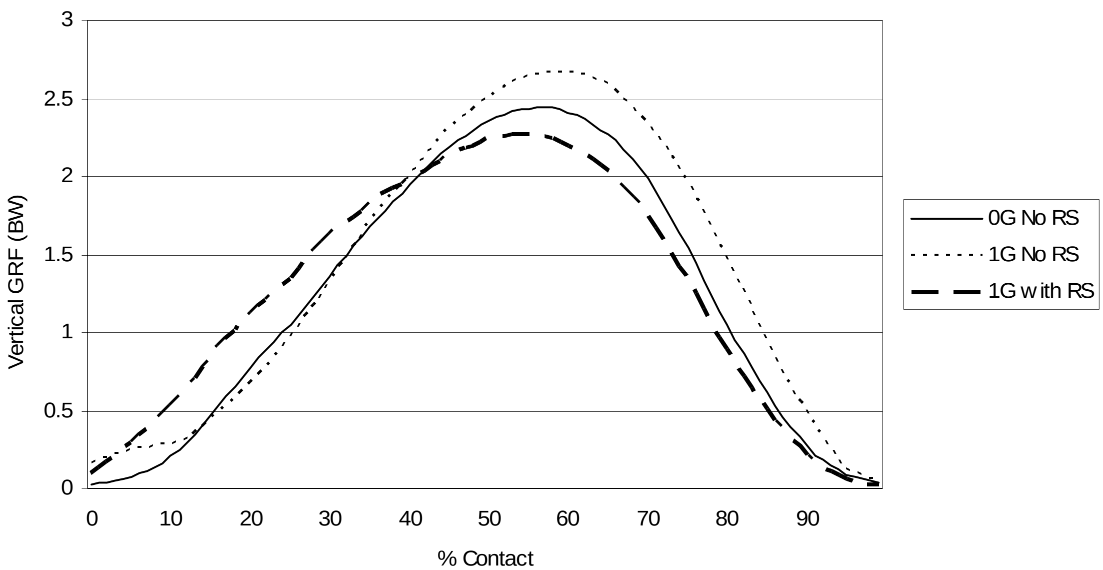


Figure 9. Typical vertical GRF trajectory during 14 km·h^{-1} locomotion in 0G and 1G on BD-1.

Peak Ground Reaction Force and Impulse

There were no significant differences in peak GRF or impulse between locomotion conditions (See Table 6). There was a significant interaction between condition and subjects during the 5 and 8 km·h^{-1} speeds in peak GRF, suggesting that the variation between conditions was different between subjects. This suggests that although the mean vertical forces developed during locomotion on the BD-1 remain similar regardless of gravitational or SLD condition, peak GRF for individual subjects may vary differently between the conditions.

Table 6. **Mean (SD) peak GRF and impulse during locomotion on the BD-1 in 0G and 1G.**

Desired Speed ($km \cdot h^{-1}$)		0G No RS	1G No RS	1G RS
5	**Peak GRF (BW)**	1.44 (0.14)	1.45 (0.15)	1.39 (0.13)
	Impulse (BW·s)	0.45 (0.05)	0.45 (0.03)	0.44 (0.05)
8	**Peak GRF (BW)**	1.84 (0.13)	1.87 (0.16)	1.88 (0.20)
	Impulse (BW·s)	0.33 (0.03)	0.32 (0.01)	0.32 (0.03)
14	**Peak GRF (BW)**	2.30 (0.15)	2.24 (0.10)	2.30 (0.01)
	Impulse (BW·s)	0.28 (0.02)	0.27 (0.02)	0.28 (0.04)

Kinematics

Five of the original eight subjects were used in the kinematic analysis. The hip marker on one subject was occluded during the 1G RS trials, causing the data to be unusable. Data from two other subjects were missing due to hardware malfunctions. Rather than using a partial dataset in which these subjects had missing data, it was decided to complete the repeated measures design using the data from the remaining five subjects. For all trials, mean peak flexion and extension and range of motion values were found for the ankle, knee and hip joints. In addition, minimum, maximum, and mean values were found for the amount of forward lean. All range of motion values were computed as the difference of the mean minimum and maximum values of the joint angle for each trial.

Qualitative Comments about Locomotion

During this investigation, it was apparent that the subjects needed to provide considerable force in order to propel the tread belt. However, it did not appear that they needed to modify their gait in 0G. Some of the subjects appeared to have difficulty achieving and maintaining the desired speed for a trial. This may have been caused by the subjects not using the entire surface of the treadmill belt. The BD-1 design is such that if the subject were to step too far forward, they could step off the front of the treadmill and tumble forward. In order to maximize the activity surface of the belt, it was necessary to land with the front foot so the heel landed on the belt, but with the forefoot extending past the front edge of the tread belt. Subjects may not have done this in fear of falling, which could have modified gait and limited their performance at high speeds.

Joint Kinematics

Figure 10-Figure 12 show typical hip, knee and ankle joint trajectories for all three conditions at each speed. The gait cycle is depicted from heel strike (0%) to the following heel strike (100%) and is the mean of a single representative trial for each condition and speed from a single subject. The general shapes of the curves are similar, suggesting that gait patterns do not differ between 0G, 1G without the RS and 1G with the RS. It appears that the general motion of the hip and ankle are similar for all speeds. However, during the 8 and 14 $km \cdot h^{-1}$ trials, after a brief period of extension, there is a reversal of knee motion followed by a return to extension.

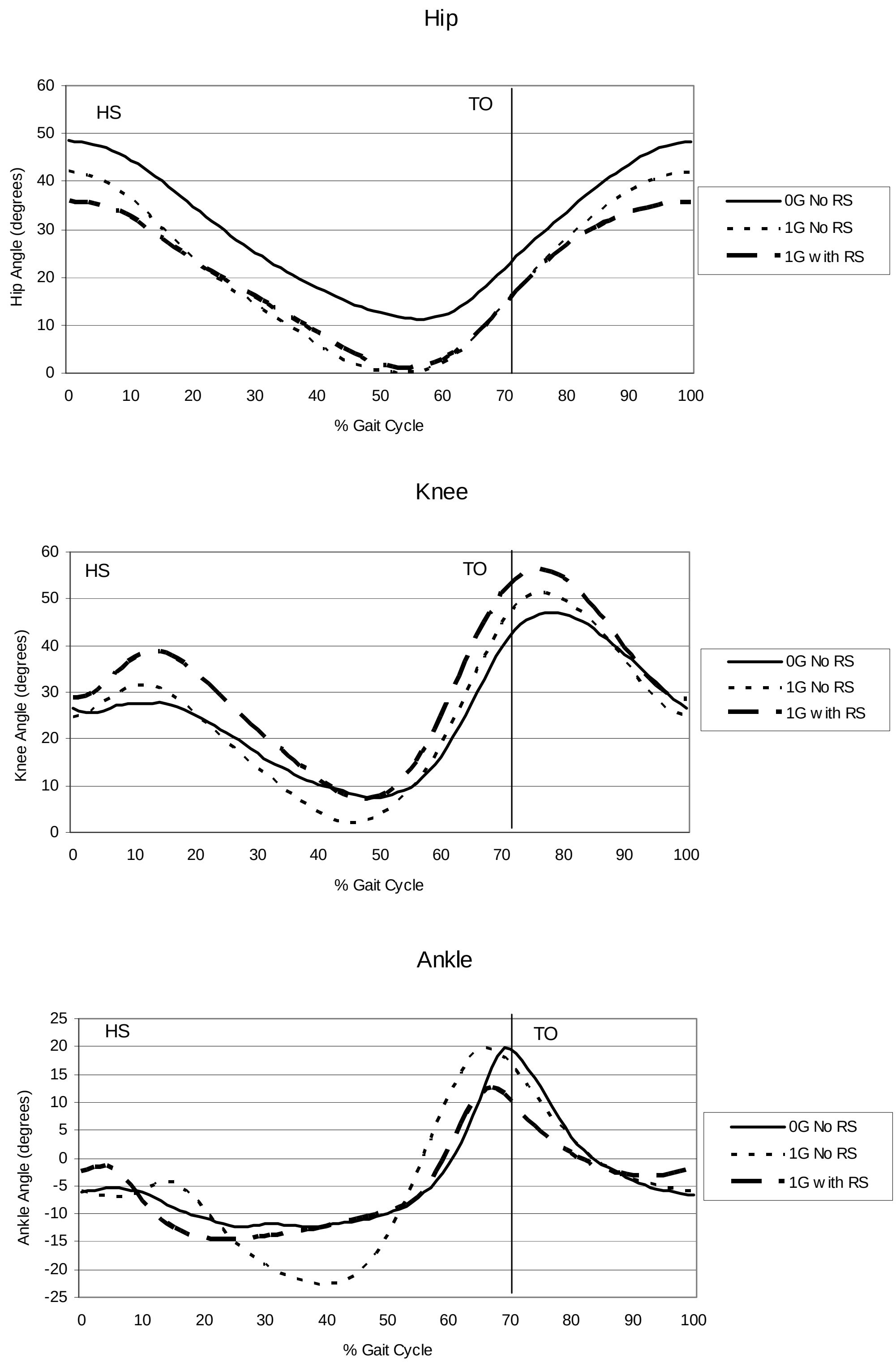


Figure 10. Typical lower extremity joint kinematics for locomotion on the BD-1 at 5 km·h^{-1}. HS = Heel Strike and TO = Toe Off.

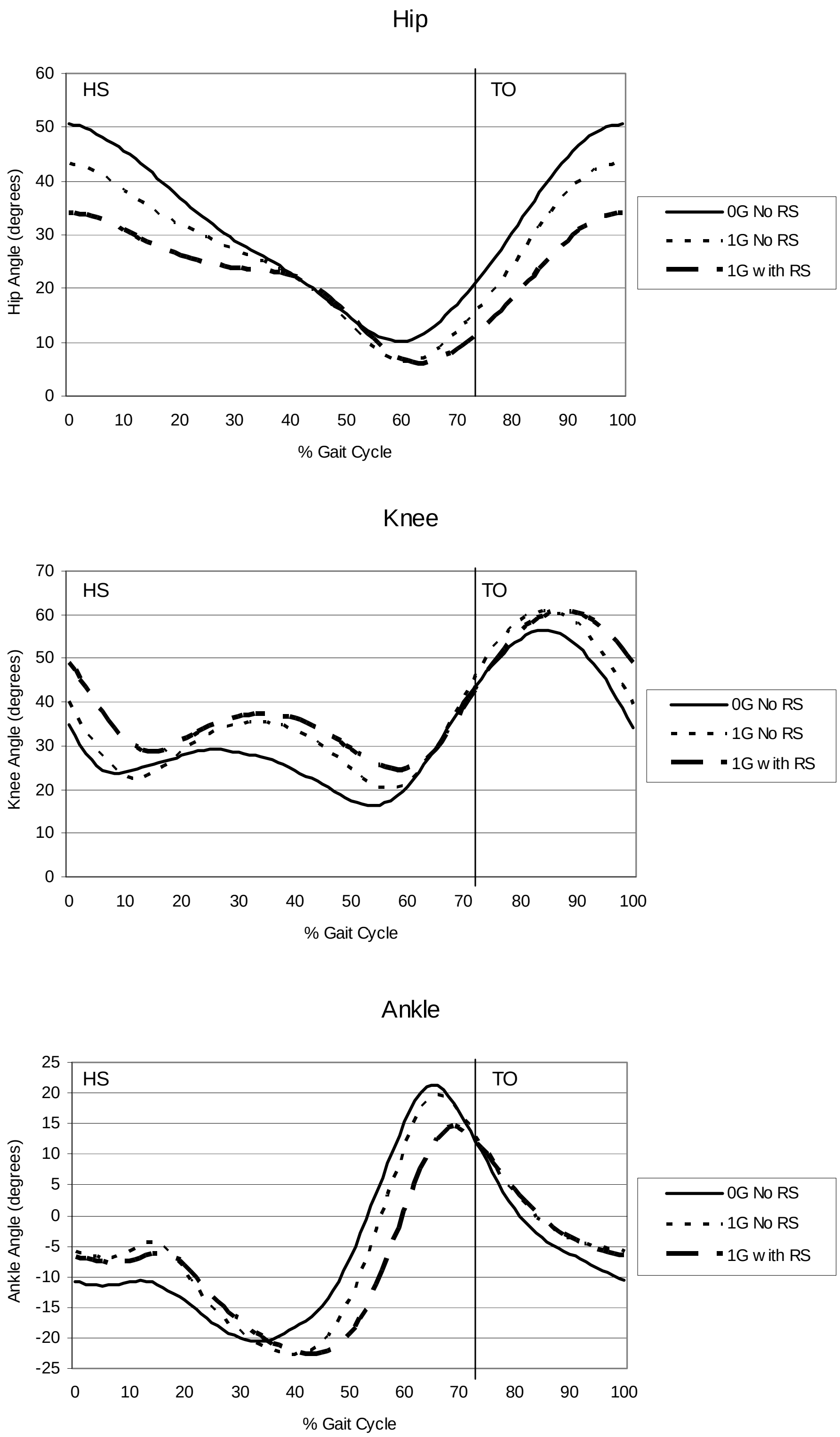


Figure 11. Typical lower extremity joint kinematics for locomotion on the BD-1 at 8 km·h^{-1}. HS = Heel Strike and TO = Toe Off. Note slight reversal of knee motion from flexion to extension at approximately 20% of the gait cycle.

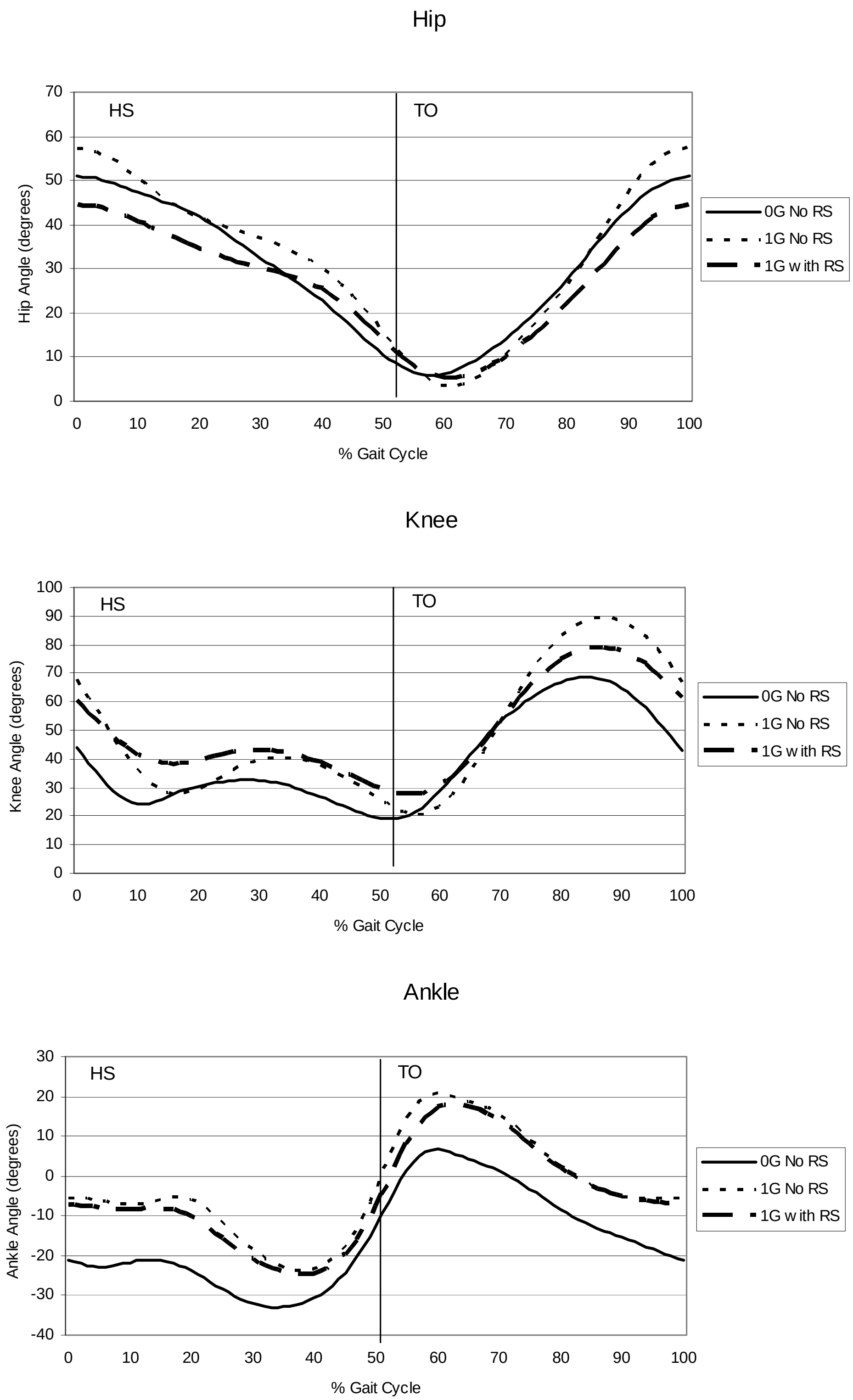


Figure 12. Typical lower extremity joint kinematics for locomotion on the BD-1 at 14 km·h^{-1}. HS = Heel Strike and TO = Toe Off. Note slight reversal of knee motion from flexion to extension at approximately 20% of the gait cycle.

Forward Lean and Joint Displacements

Table 7-Table 10 list the means and standard deviations for forward lean and each joint angle of interest. Forward lean was not computed during 0G trials due to the loss of the hip marker during that condition. The paired analysis between RS conditions for forward lean revealed that trials with the RS had less lean than without the RS for all speeds. Repeated measures ANOVAS executed within each speed for the hip, knee and ankle kinematic variables revealed no significant differences between any testing conditions for any variables. However, there were some subject interactions identified. The subject interaction suggests that although group means remained consistent, individuals may have altered their kinematics differently from condition to condition.

Table 7. Mean (SD) forward lean kinematics during locomotion on the BD-1 at all speeds.

		0G	1G	
Desired Speed ($km \cdot h^{-1}$)		No RS	No RS	RS
5	Max Forward Lean (deg)		20.91 (2.77)	19.05 (3.3)*
	Min Forward Lean (deg)		14.21 (2.53)	13.12 (3.4)
	Mean Forward Lean (deg)		18.15 (2.48)	16.71 (3.14)*
8	Max Forward Lean (deg)		27.74 (6.29)	20.43 (3.79)*
	Min Forward Lean (deg)		22.25 (5.94)	17.29 (3.76)*
	Mean Forward Lean (deg)		24.77 (6.15)	18.89 (3.69)*
14	Max Forward Lean (deg)		35.2 (7.59)	25.36 (5.02)*
	Min Forward Lean (deg)		29.39 (7.67)	20.86 (5.32)*
	Mean Forward Lean (deg)		32.43 (7.62)	23.06 (5.18)*

* Significantly different (p<.05)

Table 8. Mean (SD) hip kinematics during locomotion on the BD-1 at all speeds.

		0G	1G	
Desired Speed ($km \cdot h^{-1}$)		No RS	No RS	RS
5	Peak Hip Flexion (deg)	37.71 (10.37)	41.93 (3.45)	37.15 (1.64)
	Peak Hip Extension (deg)	0.77 (7.43)	3.3 (4.58)	2.88 (5.91)
	Mean Hip ROM (deg)	36.94 (4.81)	38.63 (4.79)	34.27 (4.38)
8	Peak Hip Flexion (deg)	41.93 (11.3)	46.4 (2.38)	38.78 (4.37)
	Peak Hip Extension (deg)	1.29 (8.03)	10.42 (9.50)	8.4 (4.74)
	Mean Hip ROM (deg)	40.64 (5.65)	35.98 (8.77)	30.38 (6.58)
14	Peak Hip Flexion (deg)	47.37 (9.27)	59.96 (4.11)	51.54 (6.86)
	Peak Hip Extension (deg)	-0.07 (8.58)	11.12 (9.50)	6.41 (4.74)
	Mean Hip ROM (deg)*	47.44 (3.48)	48.84 (11.14)	45.13 (10.04)

* Significant subject interaction (p<.05)

Table 9. **Mean (SD) knee kinematics during locomotion on the BD-1 at all speeds.**

Desired Speed ($km \cdot h^{-1}$)		0G No RS	1G No RS	1G RS
5	**Peak Knee Flexion (deg)**	57.56 (7.9)	48.77 (7.33)	53.36 (7.33)
	Peak Knee Extension (deg)*	6.57 (4.31)	0.54 (5.8)	0.85 (7.16)
	Mean Knee ROM (deg)	50.99 (6.74)	48.23 (3.64)	52.51 (3.47)
8	**Peak Knee Flexion (deg)***	74.36 (10.88)	64.99 (6.67)	67.24 (6.29)
	Peak Knee Extension (deg)*	14.97 (7.46)	17.01 (4.96)	18.54 (5.01)
	Mean Knee ROM (deg)*	59.39 (15.04)	47.98 (10.47)	48.7 (9.69)
14	**Peak Knee Flexion (deg)***	84.88 (11.89)	82.16 (11.3)	87.95 (11.98)
	Peak Knee Extension (deg)*	16.64 (4.78)	19.61 (7.77)	20.29 (7.83)
	Mean Knee ROM (deg)*	68.24 (13.32)	62.55 (16.4)	67.66 (18.51)

* Significant subject interaction ($p<.05$)

Table 10. **Mean (SD) ankle kinematics (degrees) during locomotion on the BD-1 at all speeds.**

Desired Speed ($km \cdot h^{-1}$)		0G No RS	1G No RS	1G RS
5	**Peak Dorsiflexion (deg)**	-12.8 (9.51)	-10.4 (3.62)	-11.77 (2.2)
	Peak Plantarflexion (deg)	21.49 (5.81)	15.54 (3.76)	14.45 (2.62)
	Mean Ankle ROM (deg)	34.29 (6.97)	25.94 (1.28)	26.22 (1.09)
8	**Peak Dorsiflexion (deg)***	-22.2 (6.49)	-23.11 (4.57)	-23.06 (4.27)
	Peak Plantarflexion (deg)*	20.71 (7.06)	17.95 (5.47)	16.31 (1.95)
	Mean Ankle ROM (deg)	42.91 (6.8)	41.06 (4.31)	39.37 (4.36)
14	**Peak Dorsiflexion (deg)***	-24.41 (6.17)	-24.6 (2.73)	-24.11 (3.98)
	Peak Plantarflexion (deg)	18.53 (6.12)	20.99 (5.01)	20.21 (4.76)
	Mean Ankle ROM (deg)*	18.53 (6.12)	20.99 (5.01)	20.21 (4.76)

* Significant subject interaction ($p<.05$)

Joint Velocities

The peak velocities of the knee and hip did not differ between conditions (Table 11). However, there were subject interactions identified that varied depending upon the speed. This suggests that the subjects may have produced different peak velocity trends from condition to condition at the different speeds. Furthermore, the difference in trends was not consistent for a specific motion (i.e. hip flexion), but rather were different for the different speeds.

Table 11. Mean (SD) peak joint angular velocities (deg•s^{-1}) during locomotion on the BD-1.

Desired Speed (km·h^{-1})		0G	1G	
		No RS	No RS	RS
5	Hip Flexion*	156.92 (19.39)	154.07 (21.3)	164.14 (14.23)
	Hip Extension	-131.67 (17.1)	-125.57 (22.68)	-113.57 (15.45)
	Knee Flexion	339.86 (65)	324.35 (21.31)	364.61 (14.66)
	Knee Extension	-221.54 (44.72)	-222.14 (29.15)	-263.76 (28.37)
8	Hip Flexion*	218.34 (25.23)	210.46 (44.85)	186.54 (31.11)
	Hip Extension*	-175.07 (27.6)	-182.89 (26.96)	-174.5 (27.04)
	Knee Flexion*	415 (85.33)	373.4 (31.71)	395.92 (58.27)
	Knee Extension*	-379.47 (89.57)	-389.66 (48.35)	-390.9 (63.23)
14	Hip Flexion	306.8 (46.8)	339.67 (61.28)	308.83 (64.1)
	Hip Extension	-265.54 (48.67)	-302.24 (38.24)	-290.97 (41.72)
	Knee Flexion*	527.96 (118.23)	565.64 (133.31)	621.06 (112.22)
	Knee Extension*	-504.78 (60.46)	-527.09 (74.96)	-543.27 (75.76)

* Significant subject interaction ($p<.05$)

DISCUSSION

The primary purpose of this investigation was to examine locomotion on the BD-1 during 0G and 1G to quantify kinematic, kinetic, and external loading parameters. A secondary purpose was to compare locomotion with and without a RS to determine if locomotive kinetics and kinematics are affected. It was found that subjects were able to complete trials at 5 km·h^{-1} and 8 km·h^{-1} under all conditions, and were able to obtain running speeds of 14 km·h^{-1} in 1G. However, subjects had difficulty obtaining 14 km·h^{-1} in 0G. Mean EL varied slightly with subject leg length, but was not affected by locomotion speed. Contact time, cadence, peak ground reaction force, and impulse were not different between gravitational conditions. Group locomotion kinematics were also not different between 0G and 1G, but subject differences were identified.

One of the questions of interest in this investigation concerned the ability of the subjects to run at various speeds on the non-motorized treadmill. While the subjects could obtain and maintain gait during walking (5 km·h^{-1}) and slow jogging (8 km·h^{-1}), it was difficult for some subjects to attain sprinting speeds of 14 km·h^{-1}. There are many possible reasons for this. It is possible that during the 0G trials, there was not enough time for the subjects to attain the desired speed. It is also possible that a learning effect occurred, as all subjects completed their trials in the predefined order of 0G, 1G without the PH, and 1G with the PH. The subjects may have become better at running on the BD-1 as they completed more and more trials. Finally, it is possible that the gravitational condition had an effect upon the ability to generate high treadmill velocities.

During locomotion on the current ISS treadmill, the crewmembers may place themselves under a wide range of EL using elastic bungees, the Subject Loading Device (SLD), and the SLD in combination with bungees. The EL magnitude is typically part of the exercise prescription and varies according to the crewmember and the duration and time in their mission. On the BD-1, the load was shown to be consistent at different speeds, which suggests that either the bungee length was not affected by the body's motion during locomotion, or the displacements that occurred during locomotion were not different enough between 5 km·h^{-1} and 14 km·h^{-1} to produce a difference. It is unclear how much variability in total load would occur if the bungee were attached at different points on the harness. Because the mean EL was not affected by gait speed, it may be that changing the attachment location on the harness may also not affect the EL appreciably. These results suggest that crewmembers may not be able to modify the EL appreciably during their mission while using BD-1, and that the EL experienced by each crewmember can be approximated by their leg length. This result has important implications for exercise prescription, as the EL is taken into account during periodization schemes.

It was surprising to find that temporal and kinetic parameters did not differ between 0G and 1G locomotion (see Table 12). McCrory et al., (2002) reported overground peak GRF at 3 mph (4.8 km·h^{-1}) and 6 mph (9.7 km·h^{-1}) to be 1.24 and 2.40 BW respectively (see Table 12). Our approximate mean peak GRF for 0G and 1G of 1.4 BW at 5 km·h^{-1} appears to be greater than those obtained during overground locomotion. However, the peak GRF of 2.4 BW at 14 km·h^{-1} appears to be similar or less than those obtained at similar speeds during overground and motorized treadmill locomotion. Impulses were less during our investigation at 5 km·h^{-1} and 14 km·h^{-1} than McCrory et al. found (0.61 & 0.41 BW·s).

Our findings were much different than Davis et al., (1996), who reported motorized and non-motorized running on a horizontal treadmill while suspended to create peak GRF forces of 688 N and 1002 N and impulses of 335 N·s and 201 N·s at speeds of 3.6 km·h^{-1} and 14.4 km·h^{-1}, respectively. Using the mean body mass of 76.2 kg from their study, these values correspond to peak GRF of 0.97 BW and 1.34 BW and impulses of 0.45 BW·s and 0.23 BW·s. It is interesting to note that while the peak GRF in our study were greater, the impulses were similar between 0G and 1G.

Table 12. Mean peak GRF found during BD-1 locomotion as compared to that reported in other studies.

Study		Speed	
	Approximate Load	Walking	Running
BD-1 (non-motorized)	0.70 BW @ 0G	1.40 BW @ 5 km·h^{-1}	2.40 BW @ 14 km·h^{-1}
McCrory et al. (2002)	1G	1.24 BW @ 4.8 km·h^{-1}	2.40 BW @ 9.7 km·h^{-1}
Davis et al. (1996)*	0.60 BW @ horizontal suspension	0.92 BW @ 3.6 km·h^{-1}	1.34 BW @ 14.4 km·h^{-1}

* Approximate values for a 76.2 kg subject

Our GRF values appear to be more comparable to that of overground locomotion in 1G than to non-motorized locomotion during horizontal suspension. It is possible that the horizontal orientation of the subject affected the necessary biomechanics to propel the treadmill. Our study measured GRF during upright locomotion in 1G while Davis et al. studied locomotion while subjects were suspended in a supine position. During horizontal suspension, subjects probably do not need to be concerned with balance, as it is impossible to stumble or fall. However, during upright locomotion, this must be taken into account. It is possible that gait biomechanics are altered, and are fundamentally different between horizontal suspension and upright locomotion.

A limitation to our study was that only vertical GRF could be measured. It is quite probable that significant horizontal forces are necessary to create the motion of the treadmill belt. Contact times may explain the differences in GRF and impulses between our study and McCrory et al. Those recorded in our study were consistent for each condition, but were less than those found by the other investigators. It is possible that upright running may result in different temporal patterns than suspended running.

As BD-1 belt speed increased, peak GRF increased while contact time and impulse decreased. Because impulse is dependent upon peak GRF and contact time, this result implies that the decrease in contact time was greater than the increase in peak GRF as speed increased. It is possible that the actual GRF was slightly greater than the reported vertical GRF since the fore-aft GRF may increase as treadmill speed increases. It should also be noted that the mean speeds attained during the fastest trials in 0G were less than those attained in 1G. It may be that greater forces would have occurred in 0G had the subjects attained a higher treadmill speed.

Although no data were collected during overground or motorized treadmill locomotion, results suggest that non-motorized treadmill locomotion is markedly different than motorized treadmill locomotion, probably due to the differences in task requirements. These differences may lead to different training effects when compared to long-term treadmill training on a motorized treadmill. GRF trajectories were absent of the initial impact peak reported in studies examining GRF during motorized treadmill exercise (Schaffner et al., 2005; McCrory et al., 2004). The initial peak, also known as the impact peak, occurs as the heel contacts the ground and is thought to be important for bone density maintenance because it provides a higher initial rate of change of force (Turner, 1998). The absence of this peak suggests that non-motorized treadmill locomotion may not create as great a stimulus for bone remodeling as motorized treadmill exercise. However, the increased GRF may compensate for this loss.

With regard to kinematics, it is not surprising that 1G trials without the RS resulted in greater forward lean values than those with the PH. However, it appears that lower body kinematics were not affected because there were no differences found in the hip, knee or ankle motion between these two conditions during the repeated measures analysis. Thornton et al., (1997) do not present quantitative data, but mentioned that during 0G locomotion on a non-motorized treadmill, subjects exhibited greater amounts of forward lean as speed increased, which agrees with our data. It appears that there was little difference in mean forward lean between speeds during the RS trials. Future research is necessary to determine how the approximate mean forward lean of 20 degrees compares to overground and treadmill running. However, because there were no differences in lower body kinematics between RS conditions, it also appears that the RS had little effect upon lower body motion during non-motorized treadmill running.

While it is difficult to assess the meaning of the range of motion and actual extremes of hip, knee and ankle flexion/extension, it is possible to make a few general statements. The mean hip ROM of approximately 40-45 degrees occurred as a flexor movement; the hip rarely exhibited any type of extension, probably due to the extreme forward lean of the subject. Novacek (1998) presented data during sprinting that showed typical hip range of motion of approximately 10 degrees. These data suggest that considerably more hip flexion occurs during non-motorized running, possibly due to the increased necessity to generate propulsive forces. The increased hip motion could result in overuse injuries of the quadriceps and other hip flexor/extensor musculature after prolonged exercise and should be noted by medical and training personnel.

Knee ROM appeared to increase with locomotion speed. The ROM at 14 $km \cdot h^{-1}$ of about 70 degrees was less than Novacek's (1998) values of about 95 degrees during overground sprinting. The overground data suggest that near toe-off and heel-strike, the leg is near full extension. However, the data in this investigation suggest that the knee does not extend past approximately 15 degrees of flexion. This may have occurred in order to place the foot under the body during foot-ground contact. By placing the foot under the body as opposed to in front of the body, the braking forces associated with foot-ground contact are reduced. The reduced ROM of the knee should also be noted by medical and training personnel, as it is possible that decreased hamstring flexibility could occur over time. Ankle motion is similar to that presented by Novacek (1998), suggesting that the primary differences between non-motorized treadmill and motorized or overground locomotion occur at the knee and hip joint.

Although flexion and extension velocities in each joint were not compared, it appears that at the knee and ankle, similar peak velocities were attained during both forward and rearward movements of each joint. This is especially apparent during the 14 $km \cdot h^{-1}$ trials. This reflects the importance of not only a forceful extension of the hip and knee to propel the treadmill belt, but also a forceful recovery of those joints to prepare for the next stride.

CONCLUSIONS

We found that locomotion on the BD-1 treadmill, while different than motorized treadmill gait, is not markedly different in 0G or 1G. The use of a RS reduces the amount of forward lean, but does not affect joint excursion or vertical GRF measures. Because of the non-motorized nature of the treadmill, the subjects must provide considerably greater hip, knee and ankle extensor forces during the propulsive motion. The differences in joint excursions and required forces to run on the BD-1 may require an adjustment in the overall exercise prescription, including prescriptions for other exercise modalities, provided to crewmembers to accommodate for the long term physiological effects of training upon the device, which are not yet understood.

REFERENCES

Cavanagh PR, Buczek FL, Milliron MJ. (1987).The kinematics of locomotion in space: A final report to Krug International.

Cullen DM, Smith RT, Akhter MP. (2000). Time course for bone formation with long-term external mechanical loading. Journal of Applied Physiology, 88:1943-8.

Davis BL, Cavanagh PR, Sommer III HJ, Wu, G. (1996). Ground reaction forces during locomotion in simulated microgravity. Aviation, Space, and Environmental Medicine, 67(3): 235-42.

DeWitt JK, Schaffner G, Blazine K, Bentley JR, Laughlin MS, Loehr JA, Hagan RD. (2003). Loading configurations and ground reaction forces during treadmill running in weightlessness. Presented at the 2003 Annual Meeting of the American Society of Biomechanics, Toledo, OH.

DeWitt JK, Schaffner G, Laughlin MS, Loehr JA, Hagan, RD. (2004). External load affects ground reaction force parameters non-uniformly during running in weightlessness. Presented at the 2004 Annual Meeting of the American Society of Biomechanics, Portland, OR.

Gamble DJ, Bartlett RM, Jakeman PM. (1988). A comparison of non-motorized treadmill, motorized treadmill and overground running pattern, Biomechanics of Sport, 25-32.

Heinonen A, Kannus P, Sievanan H, Oja P, Pasanen M, Rinne M, Uusi-Rasi K, Vuori I. (1996). Randomised controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. The Lancet, 348:1343-7.

Judex S, Zernicke RF. (2000). High-impact exercise and growing bone: relation between high strain rates and enhanced bone formation. Journal of Applied Physiology, 88:2183-91.

Lakomy HKA. (1987). The use of a non-motorised treadmill for analysing sprint performance. Ergonomics, 30:627-37.

LeBlanc A, Lin C, Shackelford L, Sinitsyn V, Evans H, Belichenko O, Schenkman B, Kozlovskaya I, Oganov V, Bakulin A, Hedrick T, Feeback D. (2000). Muscle volume, MRI relaxation times (T2), and body composition after spaceflight. Journal of Applied Physiology, 89:2158-64.

McCrory JL, Baron HA, Balkin S, Cavanagh PR. (2002). Locomotion in simulated microgravity: Gravity replacement loads. Aviation, Space and Environmental Medicine, 76:625-31.

McCrory JL, Derr J, Cavanagh PR. (2004). Locomotion in simulated zero gravity: ground reaction forces. Aviation, Space and Environmental Medicine, 75:203–10.

Mosley JR & Lanyon LE. (1998). Strain rate as a controlling influence on adaptive modeling in response to dynamic loading of the ulna in growing rats. Bone, 23(4):313-8.

Mosley JR, March BM, Lynch J, Lanyon LE. (1997). Strain magnitude related changes in whole bone architecture in growing rats. Bone, 20(3):191-8.

Munro CF, Miller DI, Fuglevand AJ. (1987). Ground reaction forces in running: a reexamination. Journal of Biomechanics, 20(2):147-55.

Novacek TF. (1998). The biomechanics of running, Gait and Posture, 7:77-95.

Schaffner G, DeWitt JK, Bentley JR, Yarmanova E, Kozlovskaya I, Hagan RD. (2005). Effect of Subject Loading Device Load Levels on Gait, Ground Reaction Force and Kinematics during Human Treadmill Locomotion in a Weightless Environment. NASA Technical Report NASA/TP-2005-213196.

Schaffner G, DeWitt JK, Laughlin MS, Bentley JR, Hagan RD. (2004). Effect of bungee loading on ground reaction force during treadmill locomotion in weightlessness. Presented at the 75th Annual Scientific Meeting of the Aerospace Medical Association, Anchorage, Alaska.

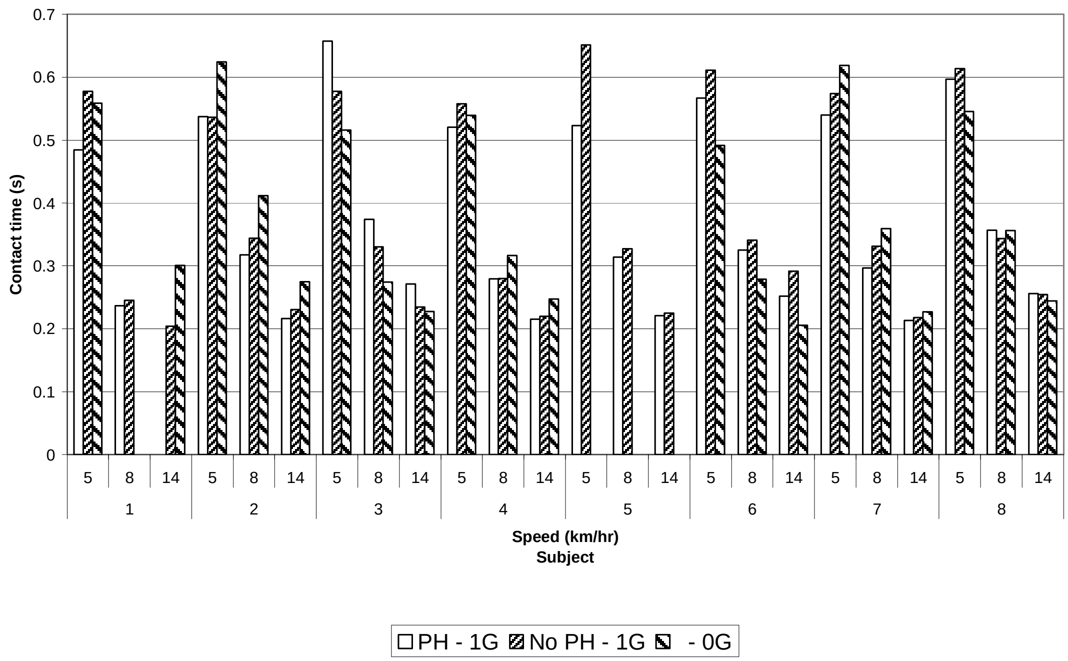
Schneider V, Oganov V, LeBlanc A, Rakmanov A, Taggart L, Bakulin A, Huntoon C, Grigoriev A, Varonin L. (1995). Bone and body mass changes during space flight. Acta Astronautica, 36(8-12):463-6.

Thornton WE, Cavanagh PR, Buczek FL, Burgess-Milliron MJ, Davis BL. (1997). The kinematics of treadmill locomotion in space. In: Allard P, Cappozzo A, Lundberg A, Vaughan CL, Eds. Three-dimensional analysis of human locomotion. 1st ed. New York: John Wiley & Sons; 1997:375-88.

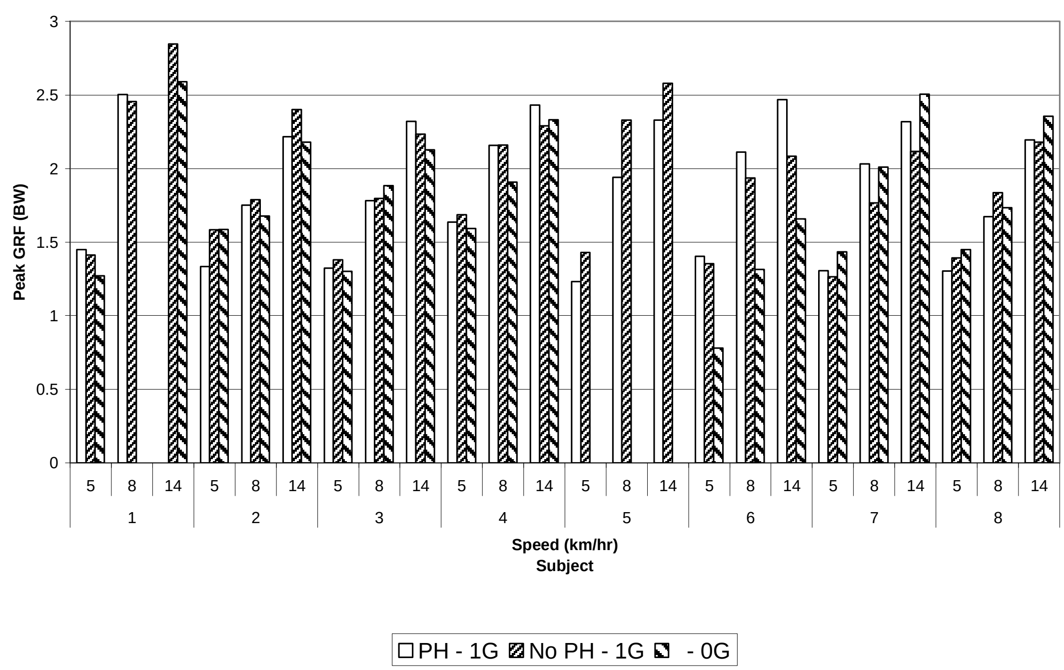
Turner CH. (1998). Three rules for bone adaptation to mechanical stimuli, Bone, 23(5):399-407.

APPENDIX

Mean contact times for all subjects - all trials



Mean Peak Ground Reaction Force for all subjects - all trials



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13. ABSTRACT *(Maximum 200 words)*

The purpose of this investigation was to evaluate locomotion on the Russian BD-1 non-motorized treadmill under three conditions weightlessness (0G) without a simulated subject positioning device, or horizontal restraint strap (RS), normal gravity (1G) without a RS, and 1G with a RS. Various outcome measures were evaluated, including the applied external load (EL), vertical ground reaction force (GRF), the ability to achieve specific locomotion speeds, and joint kinematics. The goal of this research was to better understand how locomotion and the related forces experienced by the musculoskeletal system during non-motorized treadmill locomotion in 0G compare to locomotion on the same device in 1G.

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