

Locomotion in Simulated and Real Microgravity: Horizontal Suspension vs. Parabolic Flight

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Introduction: The effect of reducing gravity on locomotion has been studied using microgravity analogues. However, there is no known literature comparing locomotion in actual microgravity (AM) to locomotion in simulated microgravity (SM). **Methods:** Five subjects were tested while walking at $1.34 \text{ m} \cdot \text{s}^{-1}$ and running at $3.13 \text{ m} \cdot \text{s}^{-1}$ on a treadmill during parabolic flight and on a microgravity simulator. The external load (EL) in AM and SM was provided by elastomer bungees at approximately 55% (low) and 90% (high) of the subjects' bodyweight (BW). Lower body joint kinematics and ground reaction forces were measured during each condition. Effect size and its 95% confidence interval were computed between gravitational conditions for each outcome variable. **Results:** In AM, subjects attained approximately $15\text{--}21^\circ$ greater hip flexion during walking and $19\text{--}25^\circ$ greater hip flexion during running. Hip range of motion was greater in AM during running by approximately $12\text{--}17^\circ$. Trunk motion was 4° less in SM than AM during walking. Peak impact force was greater in SM than in AM during walking with a low EL (SM = $0.95 \pm 0.04 \text{ BW}$; AM = $0.76 \pm 0.04 \text{ BW}$) and contact times were greater in SM. **Conclusions:** Subtle differences exist in locomotion patterns, temporal kinematics, and peak impact ground reaction forces between AM and SM. The differences suggest possible adaptations in the motor coordination required between gravitational condition, and potential differences in adaptations that are dependent upon if training occurs in actual or simulated microgravity.

Keywords: biomechanics, ground reaction forces, kinematics.

UNDERSTANDING locomotion characteristics is critical for those working in the area of exercise countermeasures for astronauts. Many researchers have investigated the effects of reducing and eliminating gravity on locomotive kinematics and kinetics (5,7,9,10). Others have studied locomotion in actual microgravity (6,13). Increased knowledge of locomotion kinematics, kinetics, and muscular activity may help to facilitate more effective exercise countermeasures to the detrimental physiological effects of long-duration spaceflight.

Data can be collected directly from astronauts during spaceflight, but studying locomotion in actual microgravity is difficult and expensive (4). The drawbacks to spaceflight experiments include difficulty in using necessary data collection hardware, and completing an experiment with adequate sample size. Parabolic flight offers a viable alternative, but periods of microgravity are limited to 20–30 s, which only allows for acute locomotion investigations.

The recognition of these limitations has led to the development of ground-based simulators that provide

relatively low-cost, longer trial durations of microgravity than parabolic flight. Horizontal suspension locomotion is an analogue used to study locomotion in conditions similar to microgravity. With this analogue, the supine subject is suspended by cables and the treadmill is oriented vertically, parallel to the direction of gravity. The system is arranged so that no gravitational forces are oriented between the treadmill surface and the subject, thus simulating microgravity. Researchers have used this arrangement to study the effects of load and harness treatments upon locomotion in microgravity (5,7,9).

Numerous studies support the validity of horizontal suspension locomotion as an analogue for microgravity (4,5,7,9,10); however, there are no known studies that compare locomotion in actual and simulated microgravity. Although the horizontal suspension model allows the subject to be oriented perpendicular to the gravity vector and the limbs are supported, locomotion still occurs in a gravitational field. In addition, because the weight of the trunk is supported by a cradle, trunk and limb motion may be fundamentally different than in actual or normal gravity. Finally, although the limbs are supported with elastic cables, it is possible that cable tension variations result in differing muscle activation requirements than during upright locomotion. Differences in motion may be related to differences in ground reaction forces (GRF). If researchers are going to use horizontal suspension locomotion to simulate microgravity, it is critical that the differences between simulated and actual microgravity conditions be quantified.

The primary purpose of this investigation was to determine the similarities and differences between locomotion in simulated microgravity (SM) and actual microgravity (AM). We hypothesized that 1) trunk motion would decrease in SM, therefore causing differences

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in hip kinematics between environments; and 2) GRF would not be different between SM and AM.

METHODS

Subjects

Five subjects (two men/three women; height 164.6 ± 9.9 cm; weight 61.3 ± 14.6 kg; age 36.2 ± 2.6 yrs; mean \pm SD) participated in this study. None of the participants had any history of lower limb injury. The procedure was approved by the NASA-Johnson Space Center Committee for Protection of Human Subjects and all subjects signed an informed consent.

Experimental Venues

All SM trials were conducted in the Exercise Countermeasures Laboratory at NASA Glenn Research Center (Cleveland, OH). SM trials occurred using the enhanced Zero Gravity Locomotion Simulator (eZLS). During SM locomotion, subjects were suspended horizontally while performing locomotion on a vertically mounted motorized treadmill. The eZLS is similar to the horizontal suspension treadmill used in previous SM studies (5,7,9,10). In the eZLS, bungee cables are attached to each limb in order to counterbalance their respective weights.

All AM trials were collected during parabolic flight onboard the NASA DC-9 aircraft managed by Johnson Space Center and based at Ellington Field (Houston, TX). Each parabola allowed for 15–25 s of microgravity alternated with 45–90 s of normal and hypergravity (3), and each flight consisted of 40 parabolas. Data from up to two subjects were collected during each of four flights. SM trials were completed approximately 2 mo earlier than the AM trials. The timeframe of the experiment was not under the control of the investigators.

Experimental Set-Up

Upon arrival to the testing facility, each subject donned spandex running tights. During the SM trials, the subjects also wore a protective helmet. Subjects wore a waist and shoulder harness to which elastomer bungees were attached to draw the subject toward the treadmill belt. The harness was made with fabric and is similar to that currently used by crewmembers onboard the International Space Station. Each subject adjusted the harness to their own comfort level so that the load was borne by the shoulders and hips. However, there was no attempt to standardize the load distribution between the waist and shoulders across subjects. The same harness was used in both testing venues.

Lower body and trunk kinematics were measured at 60 Hz with a multicamera motion capture system (Smart Elite motion capture system, BTS Bioengineering Spa, Milan, Italy). Reflective markers were attached to the subjects' left side. Markers were placed on the lateral neck level with the fifth cervical vertebrae, the posterior heel on the rear of the running shoe, and on the tip of the shoe over the distal end of the second metatarsal. Additional markers were placed on the proximal and distal lateral tibia and lateral femur to approximate the long

axes of the lower and upper leg. A final marker was placed on the harness near the greater trochanter and was used along with the neck marker to approximate the long axis of the trunk. A static trial was recorded prior to any locomotion trials while the subject held each joint in the anatomical neutral position.

Vertical GRF data were collected during the testing trials in AM with a force-measuring treadmill (Kistler Gaitway, Amherst, NY) at 480 Hz. Vertical GRF were collected at 960 Hz during SM trials with a force platform mounted beneath the treadmill belt (9287BA, Kistler, Amherst, NY). Prior to data collection each day, each subject was weighed to allow normalization of GRF data to bodyweight (BW).

External Loading

An external load (EL) was required during the AM and SM trials to return the subjects to the treadmill during each stride, and to provide gravity-like resistive force. Elastomer bungees and carabiner clips similar to those currently used by astronauts onboard the International Space Station were arranged bilaterally and connected to a waist and shoulder harness to deliver the EL. EL levels were selected to envelope the common range currently used by astronauts during long-term spaceflight and were verified during quiet standing on the instrumented treadmill.

During the low EL trials, subjects were loaded to approximately 57% of their BW (SM = $58.0 \pm 3.9\%$ BW; AM = $56.2 \pm 6.3\%$ BW). During the high EL trials, subjects were loaded to approximately 88% of their BW (SM = $89.0 \pm 4.2\%$ BW; AM = $87.3 \pm 6.6\%$ BW). Since SM trials were completed first, the EL during AM was adjusted to match the low and high loading levels used during the SM data collection for each subject.

Because of the oscillations of the subjects normal to the treadmill that occur during locomotion and the force-length properties of the bungees, it is probable that EL levels varied during actual locomotion. Although dynamic EL was not measured in this experiment, the bungees used were also used in a prior evaluation of locomotion in microgravity conducted by our laboratory. We found EL level variations during walking and running at the same speeds used in that experiment to be approximately 15% of BW (unpublished observation). We have no reason to believe that similar load fluctuations did not occur during this evaluation.

Experimental Protocol

Subjects walked at $1.34 \text{ m} \cdot \text{s}^{-1}$ and ran at $3.13 \text{ m} \cdot \text{s}^{-1}$ during each gravity and EL condition. During the SM condition, subjects completed one 60-s trial for each speed and load condition. Trials in AM lasted approximately 15 s.

Walking trials were always completed before running trials at each EL. However, EL level was randomized across subjects. For the SM trials, a balanced randomization was used to ensure that testing orders were different for each subject. For the microgravity trials, one subject

was tested each day with the low trials performed prior to the high, while the other subject performed EL conditions in reverse order. Assignment of the EL level order was made arbitrarily with a coin flip.

Data Analysis

The first 10 strides of the left leg were analyzed in each of the SM trials. The chosen epoch began with the first heel strike of the left foot and ended with the eleventh heel strike of the left foot. For the AM trials, 5 to 10 strides were analyzed for each trial due to the short periods of microgravity. For both gravitational conditions, outcome variables were computed for each stride and then averaged to obtain trial means. Software programs written in MATLAB Version 7.2.0.232 (R2006a; MathWorks, Natick, MA) were used for the entire analysis. Processing was completed on the GRF and motion capture data separately.

Center of pressure coordinates were computed and analyzed to determine if the foot in contact with the treadmill was on the right or left side of the belt. Once left footfalls were identified, contact time, stride time, peak impact force, peak propulsive force, average loading rate, and impulse were found for each step. GRF data were not filtered because we did not want to smooth actual peaks in the force trajectory. However, all footfalls were analyzed by hand to ensure that variables were recorded accurately.

Heel strike and toe off were found as described by Chang et al. (2). Contact time was the length of time that the left foot was in contact with the treadmill during each stride, and was found as the duration between heel strike and toe off for each footfall. Stride time was the length of time between successive heel strikes of the left foot. Peak impact force was the magnitude of the first distinct peak in the vertical GRF trajectory. Peak propulsive force was the magnitude of the second distinct peak. Loading rate was the peak impact force divided by the time between heel strike and time of peak impact force. The impulse for each footfall was computed as the integral of the vertical ground reaction force trajectory over contact time. Peak impact force, loading rate, peak propulsive force, and impulse were all normalized to BW to allow intersubject comparisons.

Raw motion capture data were examined for marker dropout, which were replaced using cubic spline interpolation. The motion capture data were then filtered using a fourth-order Butterworth low-pass filter with an optimal cutoff frequency for each marker determined using an autocorrelation procedure (1). Cutoff frequencies ranged from 6–28 Hz (mean = 16.65 Hz). Motion capture data expressed in the inertial reference frame were rotated into a treadmill reference frame oriented so local axes approximated the length (x) and width (z) of the treadmill surface while the third local axis was oriented normal to the treadmill (y).

A two-dimensional kinematic analysis ensued using the x and y treadmill coordinates of each marker to approximate the sagittal plane. To accomplish this, the z local coordinates for each marker were set to zero, resulting in

a projection onto the sagittal plane. The two-dimensional analysis was conducted under the assumption that lateral motion of the lower limbs was negligible. Sagittal plane joint angle trajectories of the ankle, knee, and hip were found for each sample of every trial. Hip angle was defined as the angle separating the thigh and trunk. Knee angle was defined as the angle separating the shank and thigh. Positive hip and knee angles indicated flexion. Ankle angle was found as the angle separating the shank and foot segments. Positive ankle angles represented plantarflexion. The trunk segment angle trajectory was also found as the angle separating the trunk from the reference frame axis directed normal to the treadmill surface. All angles were corrected to the anatomical neutral position using information from the static trial.

The mean and SD of each dependent variable over all strides was found for each trial. Statistical analyses were conducted using Microsoft Excel 2007 (Microsoft Corporation, Redmond, WA). Walking and running were analyzed separately because they are distinct tasks that require different kinematics.

Due to the rather limited subject size in the sample, we decided to evaluate the means for each dependent variable by computing the bias corrected effect size (ES) and the 95% confidence interval (CI) of the ES between gravitational conditions (3,8). ES were categorized as small ($0.2 < ES < 0.5$), medium ($0.5 < ES < 0.8$), or large ($ES > 0.8$), and a difference between conditions was determined if the 95% CI did not include 0. We chose to limit our analyses to ES because the statistic allows us to measure the strength of the relationship between gravitational conditions and is useful for small sample sizes. Positive ES indicate a larger value for SM than AM.

RESULTS

Joint angle trajectories for a typical subject are shown in **Figs. 1 and 2**. Means, SD, and ES for each joint and segment kinematic measure during the high EL condition are shown in **Table I**. Hip motion in AM was greater than in SM for maximum hip flexion during running and walking (running ES = -2.0; walking ES = -2.10) and hip range of motion (ROM) during running (ES = -2.42). In the walking trials, maximum ankle dorsiflexion (ES = -1.47) and trunk segment minimum angle (ES = -1.80), maximum angle (ES = -2.87), and trunk segment ROM (ES = -6.42) were greater in AM.

Table II shows means, SD, and ES for each joint and segment kinematic measure during the low EL condition. Similar to the high EL condition, differences between gravitational conditions were found in hip and trunk segment motion. During running with the low EL, maximum hip flexion (ES = -2.94), and ROM (ES = -1.78) were greater in AM. Trunk segment minimum angle (ES = -1.39) and maximum angle (ES = -1.63) were also greater in AM. During the walking trials, maximum hip flexion (ES = -1.72), trunk segment maximum (ES = -1.75), and trunk segment ROM (ES = -2.72) were larger in AM.

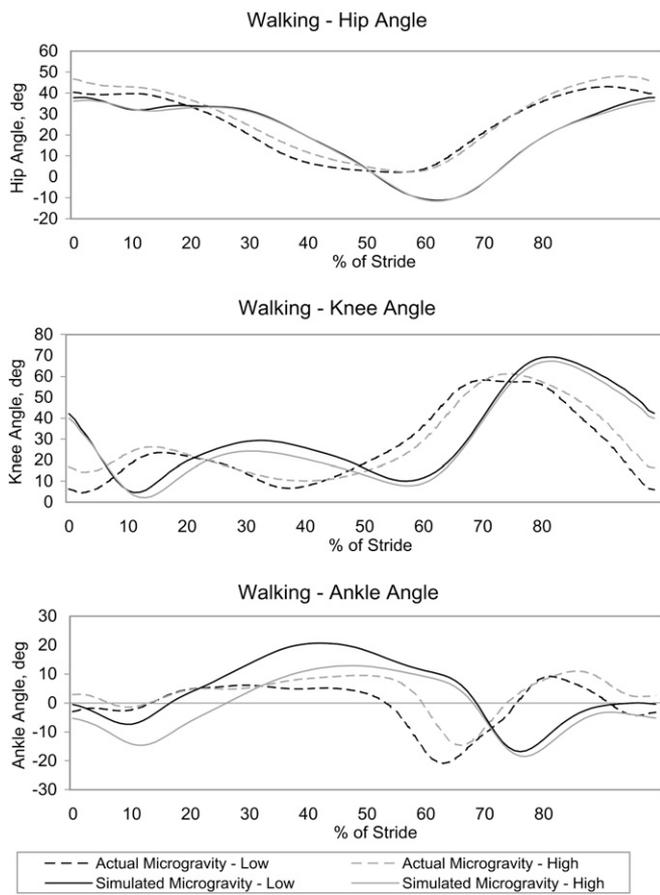


Fig. 1. Joint ensemble average trajectories for a single stride for a typical subject during walking in AM and SM.

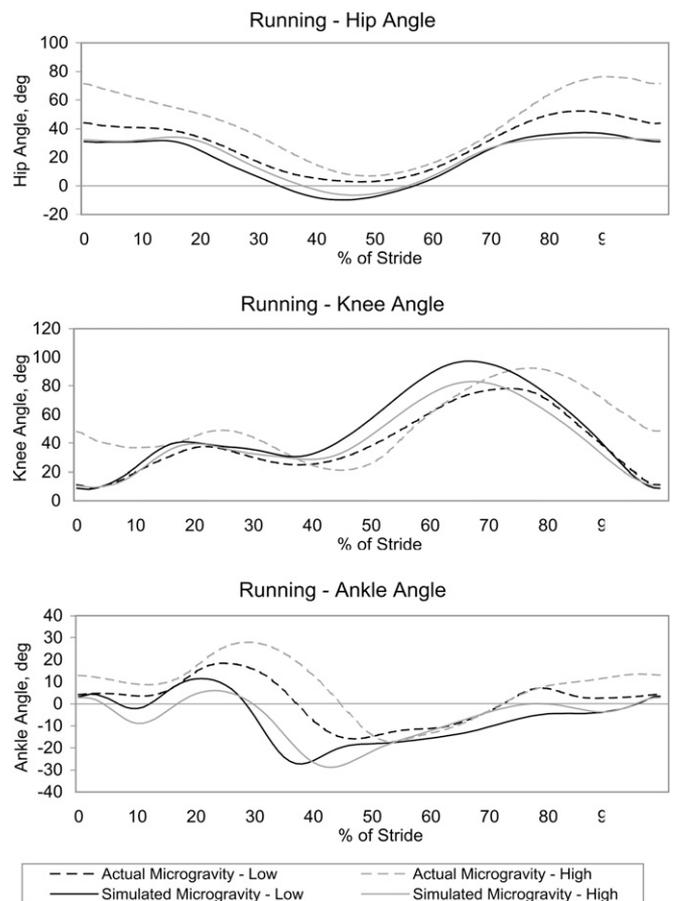


Fig. 2. Joint ensemble average trajectories for a single stride for a typical subject during running in AM and SM.

GRF and temporal kinematic data means, SD, and ES are shown in **Table III**. Impact force peaks were not discernable for two subjects during a locomotion trial on the eZLS. For one of the subjects, there were no impact peaks found during walking with low EL. For another, there were no impact peaks or loading rates found during running with high EL. Therefore, for each of these conditions, statistical analyses were completed using the remaining four subjects for peak impact force and loading rate only.

Although we found no differences in stride time between gravitational conditions, we did find longer contact times AM than SM for all loading conditions and speeds. ES for contact time ranged from 1.76 to 2.62. Most GRF variables were not different between SM and AM. Peak impact force during walking in SM during the low EL condition was greater than in AM (ES = 3.94).

DISCUSSION

While there were many similarities between gravitational conditions in kinematics, we did identify differences that could affect data interpretation and training effects on a locomotive simulator. Joint kinematic differences were identified at the hip. Maximal hip flexion angle was always greater in AM regardless of the EL or locomotive mode. Hip ROM was greater in AM during

running for both EL. Taken together, this suggests that hip motion is different in AM than SM during running, but that during walking, net hip motion may occur over different ranges of motion depending upon gravitational condition.

Hip angle was defined as the angle separating the trunk and thigh. Therefore, hip angle can change if thigh motion occurs without trunk motion, or vice versa. Differences were found in all cases except during running with a high EL, and in that case the ES was -1.33 with a 95% CI that trended toward significance $(-2.69, 0.04)$. Maximum trunk angle mean differences were approximately $9\text{--}12^\circ$ greater in AM, suggesting that more forward lean occurred in that gravitational condition. Trunk ROM was also less in SM than in AM, with significant differences during walking and non-significant, but large ES when running. Our trunk angle results suggest that the immobility of the trunk during SM locomotion, and potentially the resting position of the trunk, may result in the differences in hip kinematics between locations. If the cradle in SM were to be oriented to allow a net upward tilt of the trunk by approximately 10° from the horizontal, the differences in hip motion may be reduced. Tilting the cradle upward from the horizontal could also serve to decrease restrictions in thigh motion.

TABLE I. JOINT AND SEGMENT KINEMATIC MEASURES MEAN, SD, ES, AND 95% CI OF THE ES DURING RUNNING AND WALKING IN SIMULATED AND ACTUAL MICROGRAVITY AT HIGH EL.

| | Simulated Microgravity, Mean (SD) | Actual Microgravity, Mean (SD) | Effect Size [95%CI] | Size of Effect (If Difference Between Conditions) |
|--------------------------------|--------------------------------------|-----------------------------------|---------------------|--|
| High EL–Run | | | | |
| Hip Extension (degrees) | -15.06 (9.09) | -6.66 (15.07) | -0.61 [-1.88,0.66] | |
| Hip Flexion (degrees) | 35.18 (5.05) | 60.69 (15.50) | -2.00 [-3.51,-0.48] | Large |
| Hip ROM (degrees) | 50.24 (5.99) | 67.34 (6.72) | -2.42 [-4.06,-0.79] | Large |
| Knee Extension (degrees) | 9.66 (8.96) | 12.42 (6.33) | -0.32 [-1.57,0.93] | |
| Knee Flexion (degrees) | 86.99 (8.44) | 90.88 (8.90) | -0.40 [-1.66,0.85] | |
| Knee ROM (degrees) | 77.32 (17.15) | 78.46 (11.64) | -0.07 [-1.31,1.17] | |
| Ankle Dorsiflexion (degrees) | -28.28 (4.04) | -22.44 (8.25) | -0.81 [-2.10,0.48] | |
| Ankle Plantarflexion (degrees) | 16.13 (6.50) | 22.36 (9.82) | -0.68 [-1.95,0.60] | |
| Ankle ROM (degrees) | 44.41 (7.83) | 44.80 (3.15) | -0.06 [-1.30,1.18] | |
| Trunk Min (degrees) | -0.89 (1.19) | 9.05 (10.43) | -1.21 [-2.56,0.14] | |
| Trunk Max (degrees) | 4.36 (3.24) | 17.10 (11.83) | -1.33 [-2.69,0.04] | |
| Trunk ROM (degrees) | 5.24 (3.32) | 8.05 (2.63) | -0.85 [-2.14,0.45] | |
| High EL–Walk | | | | |
| Hip Extension (degrees) | -17.47 (7.79) | -4.52 (11.75) | -1.17 [-2.51,0.17] | |
| Hip Flexion (degrees) | 32.58 (4.64) | 53.96 (12.11) | -2.10 [-3.65,-0.56] | Large |
| Hip ROM (degrees) | 50.05 (5.49) | 58.49 (20.63) | -0.50 [-1.76,0.75] | |
| Knee Extension (degrees) | -0.80 (5.18) | 1.34 (6.95) | -0.32 [-1.56,0.93] | |
| Knee Flexion (degrees) | 57.85 (6.01) | 64.88 (9.78) | -0.78 [-2.07,0.51] | |
| Knee ROM (degrees) | 58.66 (4.74) | 63.54 (15.13) | -0.39 [-1.64,0.86] | |
| Ankle Dorsiflexion (degrees) | -20.91 (6.27) | -12.56 (3.62) | -1.47 [-2.87,-0.08] | Large |
| Ankle Plantarflexion (degrees) | 7.11 (5.60) | 13.72 (5.35) | -1.09 [-2.42,0.24] | |
| Ankle ROM (degrees) | 28.03 (3.59) | 26.28 (5.12) | 0.36 [-0.89,1.61] | |
| Trunk Min (degrees) | -0.05 (0.78) | 7.36 (5.18) | -1.80 [-3.27,-0.33] | Large |
| Trunk Max (degrees) | 1.62 (0.65) | 12.99 (5.01) | -2.87 [-4.64,-1.11] | Large |
| Trunk ROM (degrees) | 1.67 (0.31) | 5.63 (0.72) | -6.42 [-9.49,-3.35] | Large |

ES = effect size; EL = external load; ROM = range of motion. Size of effect is denoted if 95% CI did not contain 0.

It should be noted that adjustment of the trunk segment the approximate 10° as suggested would not necessarily create a scenario where hip motion was not different between gravitational conditions. Hip flexion absolute differences were on the order of 15–25°, so the trunk adjustment could bring the hip motion in each gravitational condition nearer to one another, but may not necessarily result in eliminating differences.

Examination of the hip kinematics suggests that there may be a loading effect, since maximal hip flexion absolute differences tended to be larger with high EL. Although not tested statistically, this could suggest that differences in hip kinematics between AM and SM are larger when EL approaches BW. This should be of concern for researchers who may propose studies using SM with EL near BW. If the intent of the study is to assess exercise countermeasures with the goal of loading subjects to their BW, there could be different musculoskeletal and motor adaptations occurring during SM than what would occur in AM.

Contact time was longer in SM during each type of locomotion. The differences in contact time were large, with ES ranging from 1.76–2.62. Our contact times and stride times in SM were similar to those reported by McCrory et al. (10) and Genc et al. (7). After heel-strike, the ankle will plantarflex as the foot falls flat on the treadmill belt (12). Eccentric activity of the tibialis anterior (TA) occurs during this plantarflexion (11). The increased contact time may occur because of a difference in position of the lower leg at heel strike, which may be related to increased activity of the TA. McCrory et al. (9) found

differences in knee angle at heel strike during walking and running between SM and overground locomotion. Anecdotally, subjects have reported TA local muscle soreness after SM locomotion bouts. It is possible that ankle motion and the increased contact time are related to this issue. Additionally, subjects have also reported anecdotally that having a slight forward pitch (lean) relative to the treadmill alleviates this and locomotion feels more natural.

The longer contact time in SM coupled with no differences in stride time between conditions suggests that stride lengths are less in SM than in AM. If stride time is the sum of contact time and swing time, there must be a decrease in swing time that accompanies the increase in contact time. If swing time decreases, stride length probably decreases, which could be a result of the decreased maximal hip flexion in SM. These data appear to suggest that subjects decrease stride lengths in SM by modifying hip motion during the swing phase. The swing phase in running includes two flight phases and ground contact by the opposite foot. During running, subjects decrease flight time by increasing contact time during SM. It is unclear if the decrease in flight time is a product of locomotion in SM, or if subjects purposely modify SM gait so that it occurs in a manner that is dissimilar to locomotion in AM or over ground. It is possible, however, that SM locomotion is affected by the necessary offloading equipment that causes differences specific to SM. For example, subjects do not have to be concerned with balance in SM because a majority of their weight is supported by the trunk hammock. It is possible that subjects use

TABLE II. JOINT AND SEGMENT KINEMATIC MEASURES MEAN, SD, ES, AND 95% CI OF THE ES DURING RUNNING AND WALKING IN SIMULATED AND ACTUAL MICROGRAVITY AT LOW EL.

| | Simulated Microgravity, Mean (SD) | Actual Microgravity, Mean (SD) | Effect Size [95%CI] | Size of Effect (If Difference Between Conditions) |
|--------------------------------|--------------------------------------|-----------------------------------|---------------------|--|
| Low EL—Run | | | | |
| Hip Extension (degrees) | -16.41 (7.89) | -9.82 (12.95) | -0.56 [-1.82,0.71] | |
| Hip Flexion (degrees) | 33.63 (2.85) | 52.88 (7.87) | -2.94 [-4.72,-1.15] | Large |
| Hip ROM (degrees) | 50.05 (5.82) | 62.70 (6.94) | -1.78 [-3.25,-0.32] | Large |
| Knee Extension (degrees) | 4.74 (6.67) | 7.62 (8.32) | -0.35 [-1.59,0.90] | |
| Knee Flexion (degrees) | 87.91 (11.50) | 87.09 (4.77) | 0.08 [-1.16,1.32] | |
| Knee ROM (degrees) | 83.16 (16.41) | 79.46 (7.24) | 0.26 [-0.98,1.51] | |
| Ankle Dorsiflexion (degrees) | -26.32 (5.05) | -25.68 (8.21) | -0.09 [-1.33,1.15] | |
| Ankle Plantarflexion (degrees) | 16.59 (5.65) | 23.24 (8.66) | -0.82 [-2.11,0.47] | |
| Ankle ROM (degrees) | 42.91 (9.77) | 48.92 (3.63) | -0.74 [-2.02,0.54] | |
| Trunk Min (degrees) | -0.31 (1.58) | 7.25 (6.77) | -1.39 [-2.77,-0.01] | Large |
| Trunk Max (degrees) | 3.07 (1.17) | 12.82 (7.57) | -1.63 [-3.06,-0.20] | Large |
| Trunk ROM (degrees) | 3.39 (1.54) | 5.58 (1.40) | -1.34 [-2.72,0.03] | |
| Low EL – Walk | | | | |
| Hip Extension (degrees) | -14.36 (5.29) | -9.39 (9.11) | -0.60 [-1.87,0.67] | |
| Hip Flexion (degrees) | 30.52 (6.27) | 45.61 (9.31) | -1.72 [-3.17,-0.27] | Large |
| Hip ROM (degrees) | 44.88 (7.62) | 55.00 (10.09) | -1.02 [-2.34,0.30] | |
| Knee Extension (degrees) | 2.15 (3.54) | -1.90 (3.82) | 0.99 [-0.32,2.31] | |
| Knee Flexion (degrees) | 63.34 (6.76) | 60.93 (8.61) | 0.28 [-0.96,1.53] | |
| Knee ROM (degrees) | 61.19 (4.97) | 62.83 (8.31) | -0.22 [-1.46,1.03] | |
| Ankle Dorsiflexion (degrees) | -19.82 (5.33) | -14.69 (4.69) | -0.92 [-2.23,0.38] | |
| Ankle Plantarflexion (degrees) | 11.92 (10.38) | 12.67 (8.06) | -0.07 [-1.31,1.17] | |
| Ankle ROM (degrees) | 31.74 (7.93) | 27.36 (5.96) | 0.56 [-0.70,1.83] | |
| Trunk Min (degrees) | -0.08 (1.34) | 5.57 (6.10) | -1.15 [-2.49,0.18] | |
| Trunk Max (degrees) | 1.43 (1.16) | 10.25 (6.34) | -1.75 [-3.21,-0.29] | Large |
| Trunk ROM (degrees) | 1.51 (0.44) | 4.69 (1.42) | -2.72 [-4.44,-1.00] | Large |

ES = effect size; EL = external load; ROM = range of motion. Size of effect is denoted if 95% CI did not contain 0.

this to allow unnatural locomotion for a variety of reasons, including decreased metabolic cost by reducing hip motion. This should be studied further to better understand the contributing mechanisms.

Peak impact GRF were 25% BW greater in SM during walking at low EL. We found no differences in peak propulsive forces between locations at either speed or EL level. Our peak impact forces in SM were similar to those reported by McCrory et al. (10), but our peak propulsive forces were less. Our findings in AM are consistent with Schaffner et al. (13), who reported peak impact and propulsive forces during walking in AM with EL of approximately 90% BW to be approximately 1.22 and 1.50 BW, and during running to be 0.90 and 1.94 BW, using the same speeds as in this experiment.

Researchers have speculated that the GRF that occur during impact are beneficial for bone health (14). The exact mechanism that most affects bone health has not been identified. Our results suggest that if impact force is critical, that the walking exercise in SM with lower EL could be superior to similar exercise in AM as an osteogenic stimulus. Researchers and operations personnel should, therefore, be cautious when relating the GRF findings during exercise in SM to AM. However, more data are needed to make a definitive statement.

A primary limitation in this study was the low subject size, which limited our ability to perform traditional statistical analyses. This was unavoidable given the high cost of collecting data and the infrequent opportunities to capture data during parabolic flight compounded

with the fact that test venues were located in different NASA centers. We purposely limited our data collection conditions to single speeds of walking and running to capture different locomotion modes, and only two loading levels, even though crewmembers typically exercise with multiple loading levels over the course of a mission, resulting in four test conditions per location. Even with these controls in place, we were still limited to the maximum amount of subjects that could participate in the study.

We originally started this project with eight subjects, but one was unable to complete data collection in both locations and motion capture data were lost for two subjects during the AM trials. We could have presented motion capture data for the remaining five and GRF data for seven subjects, but chose to eliminate the two subjects from all analyses for consistency purposes. Of the five subjects, lack of impact forces for two resulted in reducing the sample size to four during GRF comparisons in two of the four test conditions.

We addressed the low subject size by limiting our statistical analysis to the computation of effect size and its 95% confidence interval. We feel our approach is valid because we only discussed differences when the effect size 95% confidence interval did not include 0, suggesting that there was an actual difference between the microgravity conditions. We do acknowledge that the ES results are only for the sample studied. However, we have no reason not to believe that these results extend to the general population.

TABLE III. TEMPORAL KINEMATIC AND GROUND REACTION FORCE MEAN, SD, ES, AND 95% CI OF THE ES DURING RUNNING AND WALKING IN SIMULATED AND ACTUAL MICROGRAVITY AT HIGH AND LOW EL.

| | Simulated Microgravity | | Actual Microgravity | | Effect Size [95%CI] | Size of Effect (If Difference Between Conditions) |
|--------------------------------------|------------------------|----------------|---------------------|----------------|---------------------|---|
| | N | Mean (SD) | N | Mean (SD) | | |
| High EL - Run | | | | | | |
| Contact Time (s) | 5 | 0.41 (0.09) | 5 | 0.24 (0.03) | 2.24 [0.66,3.82] | Large |
| Stride Time (s) | 5 | 0.79 (0.10) | 5 | 0.69 (0.06) | 1.04 [-0.28,2.36] | |
| Impulse (BW · ms ⁻¹) | 5 | 284.48 (26.29) | 5 | 250.38 (18.28) | 1.36 [-0.02,2.73] | |
| Loading Rate (BW · s ⁻¹) | 4 | 40.60 (13.66) | 5 | 46.10 (18.72) | -0.29 [-1.61,1.03] | |
| Peak Propulsive Force (BW) | 5 | 1.77 (0.17) | 5 | 1.68 (0.12) | 0.50 [-0.75,1.76] | |
| Peak Impact Force (BW) | 4 | 1.73 (0.50) | 5 | 1.30 (0.26) | 1.01 [-0.39,2.40] | |
| High EL - Walk | | | | | | |
| Contact Time (s) | 5 | 0.83 (0.10) | 5 | 0.60 (0.07) | 2.49 [0.84,4.14] | Large |
| Stride Time (s) | 5 | 1.06 (0.10) | 5 | 1.03 (0.10) | 0.30 [-0.95,1.55] | |
| Impulse (BW · ms ⁻¹) | 5 | 412.65 (29.63) | 5 | 410.43 (96.85) | 0.03 [-1.21,1.27] | |
| Loading Rate (BW · s ⁻¹) | 5 | 9.50 (2.65) | 5 | 7.56 (2.68) | 0.66 [-0.62,1.93] | |
| Peak Propulsive Force (BW) | 5 | 0.83 (0.07) | 5 | 0.87 (0.16) | -0.30 [-1.55,0.95] | |
| Peak Impact Force (BW) | 5 | 1.08 (0.08) | 5 | 0.96 (0.10) | 1.18 [-0.16,2.52] | |
| Low EL - Run | | | | | | |
| Contact Time (s) | 5 | 0.35 (0.07) | 5 | 0.24 (0.03) | 1.76 [0.30,3.22] | Large |
| Stride Time (s) | 5 | 0.88 (0.17) | 5 | 0.79 (0.10) | 0.63 [-0.64,1.90] | |
| Impulse (BW · ms ⁻¹) | 5 | 236.78 (20.90) | 5 | 215.22 (21.21) | 0.92 [-0.38,2.23] | |
| Loading Rate (BW · s ⁻¹) | 5 | 23.57 (15.60) | 5 | 35.85 (15.93) | -0.70 [-1.98,0.57] | |
| Peak Propulsive Force (BW) | 5 | 1.56 (0.14) | 5 | 1.45 (0.13) | 0.77 [-0.52,2.05] | |
| Peak Impact Force (BW) | 5 | 1.38 (0.44) | 5 | 1.09 (0.25) | 0.74 [-0.54,2.02] | |
| Low EL Walk | | | | | | |
| Contact Time (s) | 5 | 0.83 (0.08) | 5 | 0.63 (0.05) | 2.62 [0.93,4.31] | Large |
| Stride Time (s) | 5 | 1.08 (0.10) | 5 | 1.10 (0.07) | -0.23 [-1.48,1.01] | |
| Impulse (BW · ms ⁻¹) | 5 | 281.00 (38.63) | 5 | 308.57 (64.15) | -0.47 [-1.73,0.79] | |
| Loading Rate (BW · s ⁻¹) | 4 | 9.82 (3.36) | 5 | 7.80 (2.90) | 0.58 [-0.76,1.92] | |
| Peak Propulsive Force (BW) | 5 | 0.72 (0.27) | 5 | 0.64 (0.19) | 0.31 [-0.94,1.56] | |
| Peak Impact Force (BW) | 4 | 0.95 (0.04) | 5 | 0.76 (0.04) | 3.94 [1.70,6.19] | |

ES = effect size; EL = external load. All ground reaction force values are normalized to the subjects' normal gravity bodyweight (BW). Size of effect is denoted if 95% CI did not contain 0.

Finally, locomotion trials that occur in AM were limited to the 20-30 s bouts available during parabolic flight. Since AM is a novel environment, it is possible that the biomechanical effects were transient and that astronauts may actually locomote differently during spaceflight in a way that allows for longer duration exercise. In addition, the fact that microgravity periods during parabolic flight are separated by normal and hypergravity conditions could result in acclimation differences that were due to parabolic flight and not microgravity. An evaluation of locomotion onboard the International Space Station is necessary to control for this effect.

This was the first study to complete a biomechanical comparison of locomotion in SM and AM using the same subjects. We hypothesized that trunk motion would decrease in SM, therefore causing differences in hip kinematics between environments, and GRF would not be different between SM and AM. We found data to support both of our hypotheses and that subtle differences occur between SM and AM locomotion in joint kinematics and GRF. When using SM, researchers should expect to observe kinematic differences from AM, including motion of the trunk and hip, increased contact time, and potential increases in GRF for a given EL. These differences could result in training adaptations that are specific to the type of microgravity (AM vs. SM)

and should be accounted for when designing and interpreting data from studies conducted using SM as the primary exercise venue with the intent of extending the results to AM.

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